Air Force Office of Scientific Research

PANEL DISCUSSION

ON

SMART STRUCTURES/MATERIALS

1 November 1991
Holiday Inn, Dayton Ohio

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REPORT DOCUMENTATION PAGE

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   This report is a summary of a panel discussion on Smart Structures/Materials, and the presentations that were included. A paper presenting the Wright-Laboratory position on the technology needs for research in Aeronautical Structural Mechanics is also included in this document. This meeting was sponsored by AFOSR and was held at Wright-Patterson AFB, Ohio on 9 October 1991.

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FOREWORD

The Air Force Office of Scientific Research (AFOSR) sponsored two contractor meetings on the "Mechanics of Materials" and "Structural Dynamics" at the Holiday Inn in Fairborn, Ohio during the week of 7 October 1991. The meetings were hosted by Mr. Robert M. Bader, Chief of the Structures Division, Flight Dynamics Directorate, Wright Laboratory at Wright-Patterson Air Force Base. The technical sessions were organized and coordinated by Dr. Spencer Wu, AFOSR Program Manager for Aerospace Sciences. A panel discussion on Smart Structures/Materials was conducted in conjunction with these meetings on Wednesday, 9 October. The session was chaired by Mr. Tony Gerardi of the Structural Integrity Branch, Structures Division, Flight Dynamics Directorate, Wright Laboratory at Wright-Patterson Air Force Base.

This report includes a summary of the panel discussion and the six technical presentations that were part of the program. A paper presenting the Wright Laboratory position on the technology needs for research in Aeronautical Structural Mechanics is also included in this report.

The administrative arrangements for the AFOSR meetings and panel discussions were conducted by the Aerospace Structures Information and Analysis Center (ASIAC), which is operated for the Flight Dynamics Directorate, Wright Laboratory by CSA Engineering, Inc. The efforts of Mr. Gordon R. Negaard, ASIAC Technical Manager, and all the ASIAC staff for coordinating and arranging the meeting details are greatly acknowledged.

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SECTION I

SMART STRUCTURES PANEL
DISCUSSION SUMMARY

Mr. Tony Gerardi

Principal Scientist

Structural Integrity Branch

Structures Division

Flight Dynamics Directorate

Wright Laboratory

United States Air Force

Wright-Patterson Air Force Base, Ohio

PANEL DISCUSSION SUMMARY

Dr Wu preceded the panel discussion with an introduction and an overview of the panel's purpose. This overview was followed by five excellent technical presentations. One paper from each of the panelists as follows:

Dr. Edward F. Crawley (MIT) "Progress in Intelligent Structures"

Dr. Eric Cross (Penn State) "Piezoelectric Ceramics "

Dr. Dan Inman (Univ. at Buffalo, SUNY) "Panel Discussion on Smart Structures/Materials"

Dr. Craig Rogers (VPI) " Characterization and Modeling of PZT"

Dr. Terrance Weisshaar (Purdue) "Active Composite Structures"

A copy of each presentation is contained in Section II of this report. Mr. Tony Gerardi of the Structures Division of Wright Laboratory gave a brief overview of Air Force needs in the area of air vehicle structures and Mr. Monte Smith presented a review of the ongoing programs at Phillips Laboratory. The meeting was then opened for discussion. Mr Gerardi served as panel moderator and each of the panel members answered questions from the floor.

The meeting was successful in relating state of the art technology in several specific areas in the broad Smart Materials/Structures field. In addition, the stimulating discussion involving experts in their respective fields identified several specific areas where "gaps" are beginning to appear. One is "integration". The term integration surfaced several times during the discussion. Typically little integration can occur until a well defined goal is established. Mr Gerardi commented that now may be the appropriate time to begin thinking about an agreed upon goal and an agency to manage it. One goal could be a Smart Vehicle Technology Demonstrator (SVTD) designed to provide a platform for tieing the various technologies together and operationally testing them as a system. Another possibility could be a multi-

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agency "Smart Laboratory" designed for the same purpose. Once the desired capabilities of our goal are well defined, integration can occur.

As one of the primary purposes of the panel discussion was to provide direction for 6.1 future efforts in the Smart Structures/Materials area for aerospace vehicles, a paper by Dr. James Olsen, chief scientist of the Flight Dynamics Directorate, of Wright Laboratory is also included as Section III of this report. This paper was prepared to summarize the technology needs for research in aeronautical structural mechanics. The document cuts across the 6.1, 6.2, and 6.3 pockets of research and contains explanations of problems, unknowns and science issues in aeronautical structures. Most of the issues identified are related, either directly or indirectly, to "smart" technology. Hopefully, this document, in conjunction with the panel discussion, will be useful in providing the guidance needed for future 6.1 research. Finally, AFOSR will have an FY 93 initiative on Smart Structures/Materials addressing the development of smart skins for air vehicles. The purpose of the initiative is to create methods that will control air turbulence and produce favorable loading conditions on an aircraft.

SECTION II

PANEL DISCUSSION

ON

SMART STRUCTURES/MATERIALS

TECHNICAL PRESENTATIONS

Dr. Spencer T. Wu
Program Manager, Aerospace Sciences
Air Force Office of Scientific Research
Bolling Air Force Base
"Introduction and Overview"

Dr. Edward F. Crawley
Space Engineering Research Center
Massachusetts Institute of Technology
"Progress in Intelligent Structures"

Dr. Eric Cross
Pennsylvania State University
"Pietzoelectric Ceramics"

Dr. Dan Inman
University at Buffalo
State University of New York
"Panel Discussion on Smart Structures/Materials"

Dr. Craig Rogers
Virginia Polytechnic Institute and State University
Characterization and Modeling of PZT

Dr. Terrance Weisshaar
Purdue University
"Active Composite Structures"

TECHNICAL PRESENTATION

"Introduction and Overview"

BY

Dr. Spencer T. Wu

Program Manager, Aerospace Sciences

Air Force Office of Scientific Research

Bolling Air Force Base

PANEL DISCUSSION ON SMART STRUCTURES/MATERIALS -- S. WU

PANELISTS:

E.F. CRAWLEY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY

L.E. CROSS, THE PENNSYLVANIA STATE UNIVERSITY

D.J. INMAN, STATE UNIVERSITY OF NEW YORK

A. GERARDI, WRIGHT LABORATORY

C.A. ROGERS, VIRGINIA POLYTECHNIC INSTITUTE

T.A. WEISSHAAR, PURDUE UNIVERSITY

AFOSR'S PRESENT PROGRAM INCLUDES

- AEROSERVOELASTIC TAILORING

- OPTIMIZED SENSOR/ACTUATOR/PROCESSOR SYSTEMS

- MODELING OF MECHANICAL-ELECTRIC FIELD EFFECTS IN PIEZOELECTRIC MATERIALS (DOMAIN PROCESSES IN PZT)

- STRUCTURE-MATERIAL INTERACTION ANALYSIS

- NONLINEAR CONTROL OF THE FLEXIBLE STRUCTURES

THIS PANEL SESSION INCLUDES

- PRESENTATIONS OF STATE-OF-THE-DEVELOPMENT IN SMART
  STRUCTURES/MATERIALS AREA

- DISCUSSIONS OF SYSTEMATIC APPROACHES FOR DEVELOPING
  OPTIMIZED SENSOR/ACTUATOR/PROCESSOR NETWORKS

- IDENTIFICATION OF NEW (BASIC) RESEARCH ISSUES (FOR IMPROVING
  PERFORMANCE/CONTROL DESIGN OF FUTURE AIR FORCE AIRCRAFTS
  AND SPACE STRUCTURES)

8

AFOSR'S CURRENT EFFORTS

- DETECTION/EXAMINATION OF PRECURSOR BEHAVIOR TO FAILURE

- COMPLEMENTARY DIAGNOSIS/CHARACTERIZATION DEVICES

- INTEGRATED NDE THEORY AND EXPERIMENT DEVELOPMENT

- FATIGUE AND HYSTERESIS CORRELATION

TECHNICAL PRESENTATION

"Piezoelectric Ceramics"

BY

Dr. Eric Cross

Pennsylvania State University

DEFORMATION OF A CRYSTAL SUBJECTED
TO ELASTIC STRESS AND ELECTRIC FIELD

$$x_{ij} = s_{ijkl} X_{kl} + d_{mij} E_m + M_{mnij} E_m E_n.$$

PIEZOELECTRICITY

CRYSTAL SYMMETRY SUCH THAT
SOME $d_{mij} \neq 0$ Then for $X_{kl} = 0$

Actuating $x_{ij} = d_{mij} E_m$ Linear relation

x changes sign

Sensing $P_m = d_{mij} X_{ij}$ when E changes sign

ELECTROSTRICTION

CRYSTAL SYMMETRY SUCH THAT
ALL $d_{mij} = 0$ (CENTRIC CRYSTAL).

$$x_{ij} = M_{mnij} E_m E_n \quad \text{For } X_{kl} = 0$$

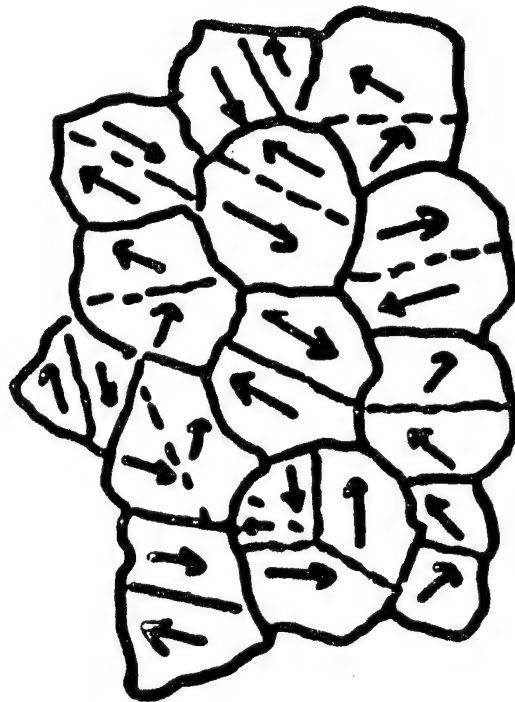$$\eta_{mn} = M_{mnij} X_{ij}$$

PIEZOELECTRIC COEFFICIENTS

x_3

x_1

Ti

Pb

O
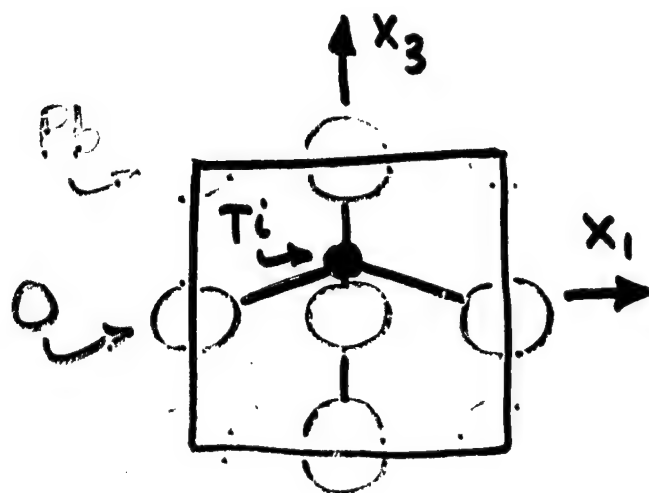
PbTiO₃
SYMMETRY 4mm

σ_3

$$\Delta P_3 = d_{33}\, \sigma_3$$
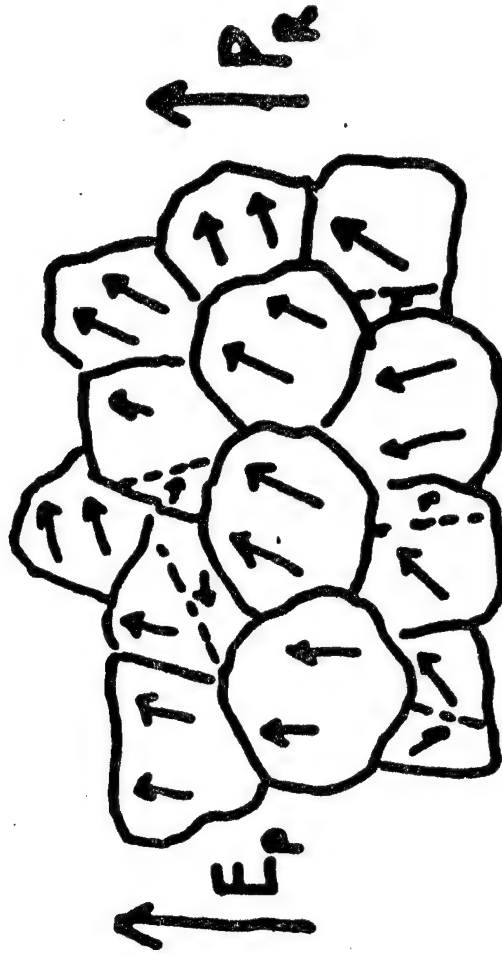
σ_1

$$\Delta P_3 = d_{31}\, \sigma_1$$

σ_5
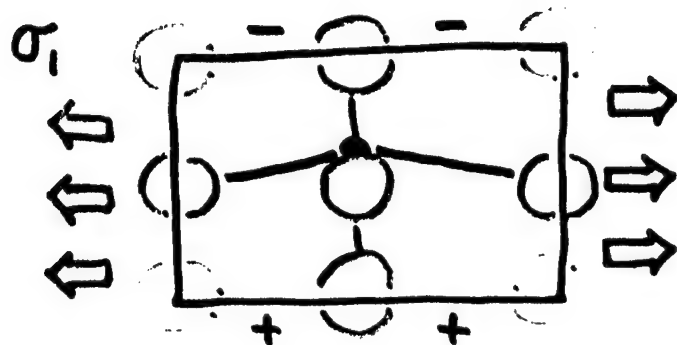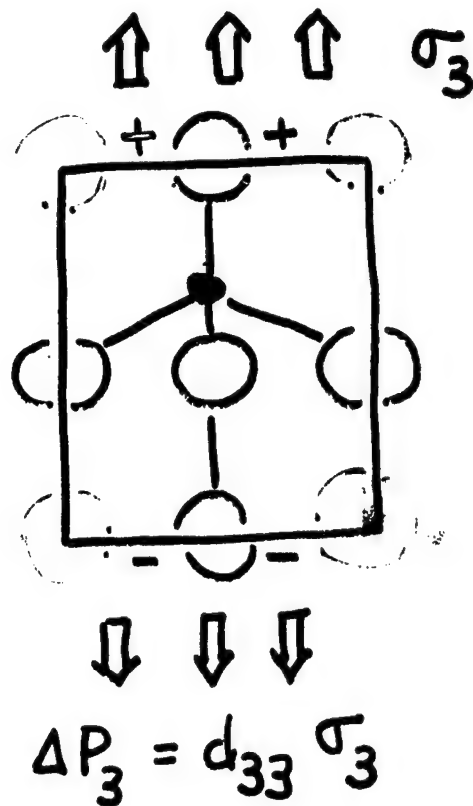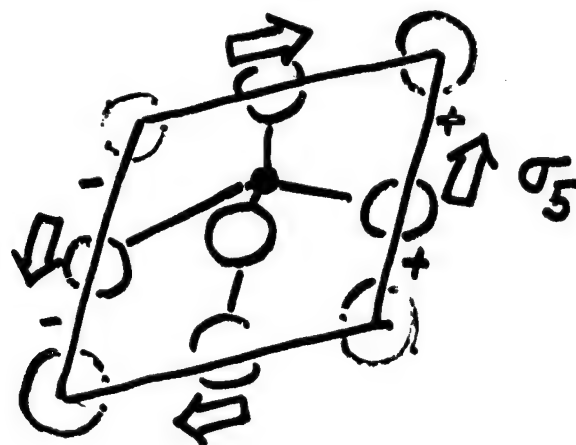
$$\Delta P_1 = d_{15}\, \sigma_5$$

FERROELECTRIC

Unpoled

Poling

P_R

E_P

E_P

P_R
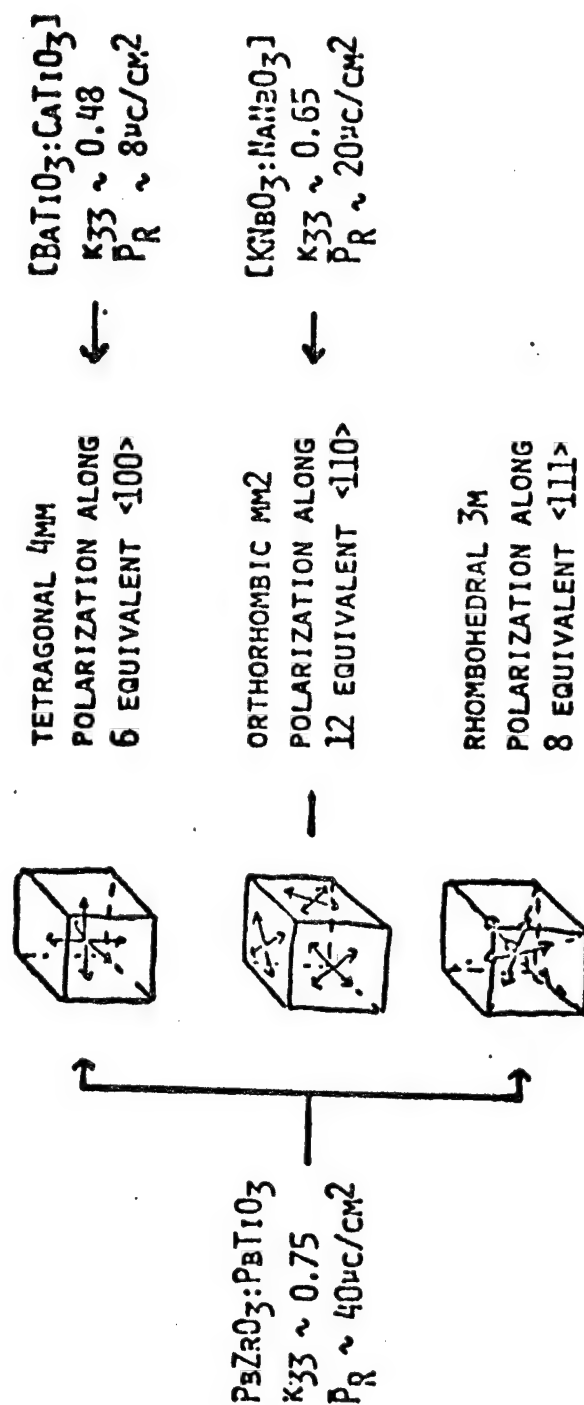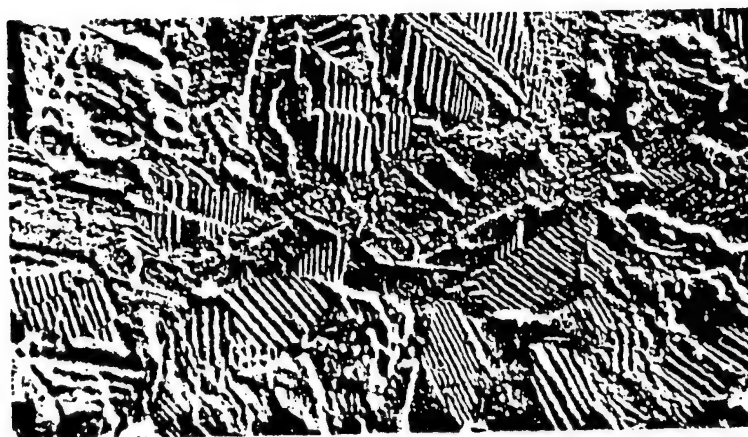
TEXTURE SYMMETRY

CURIE GROUP ∞mm.

13
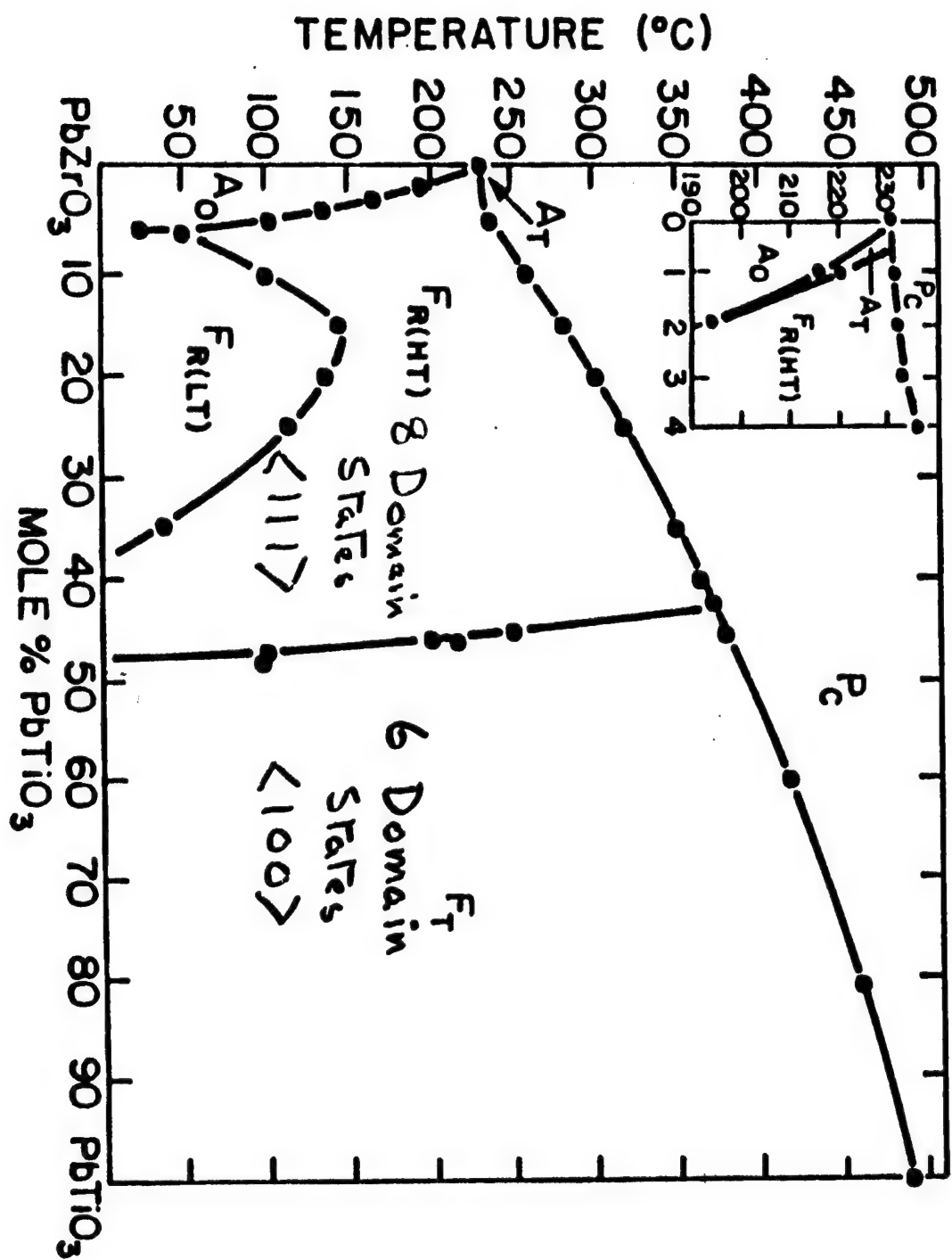
POSSIBLE ORIENTATION STATES IN PEROVSKITES

TETRAGONAL 4MM
POLARIZATION ALONG
6 EQUIVALENT <100>

$[BaTiO_3:CaTiO_3]$
$K_{33} \sim 0.48$
$P_R \sim 8 \mu c/cm^2$

ORTHORHOMBIC MM2
POLARIZATION ALONG
12 EQUIVALENT <110>

$[KNbO_3:NaNbO_3]$
$K_{33} \sim 0.65$
$P_R \sim 20 \mu c/cm^2$

RHOMBOHEDRAL 3M
POLARIZATION ALONG
8 EQUIVALENT <111>

$PbZrO_3:PbTiO_3$
$K_{33} \sim 0.75$
$P_R \sim 40 \mu c/cm^2$

15
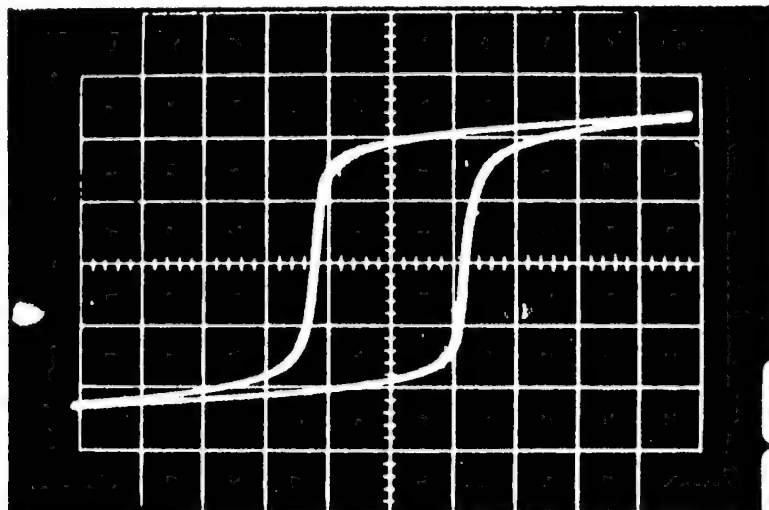
Electron micrograph of (a) unpoled and (b) poled Nb-modified
Pb(Ti, Zr)O$_3$.[32] Note the relative absence of both 90° and 18 0° domain bound-
aries in the poled sample.
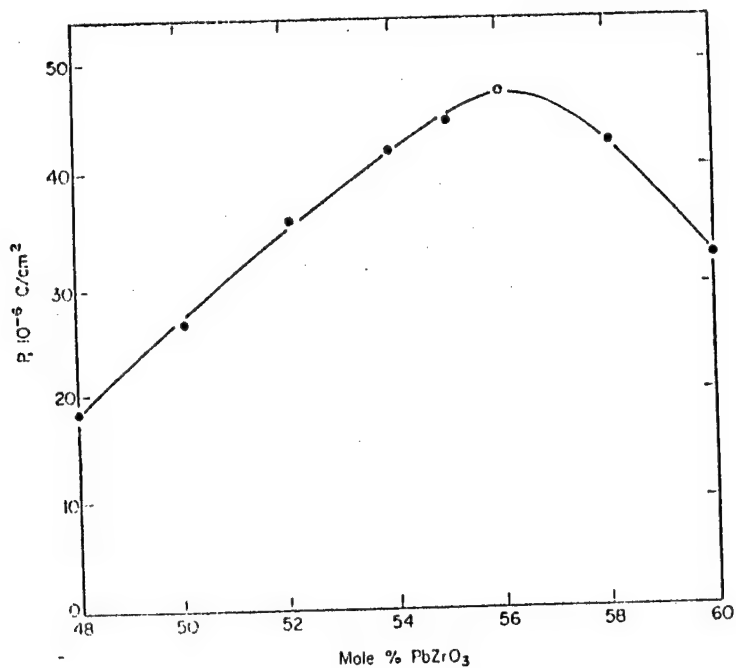
Remanent polarization as a function of composition for Pb(Ti, Zr)O₃ near the morphotropic phase boundary.[15] Figures represent total charge released into a short circuit load under axial compression at 25°.
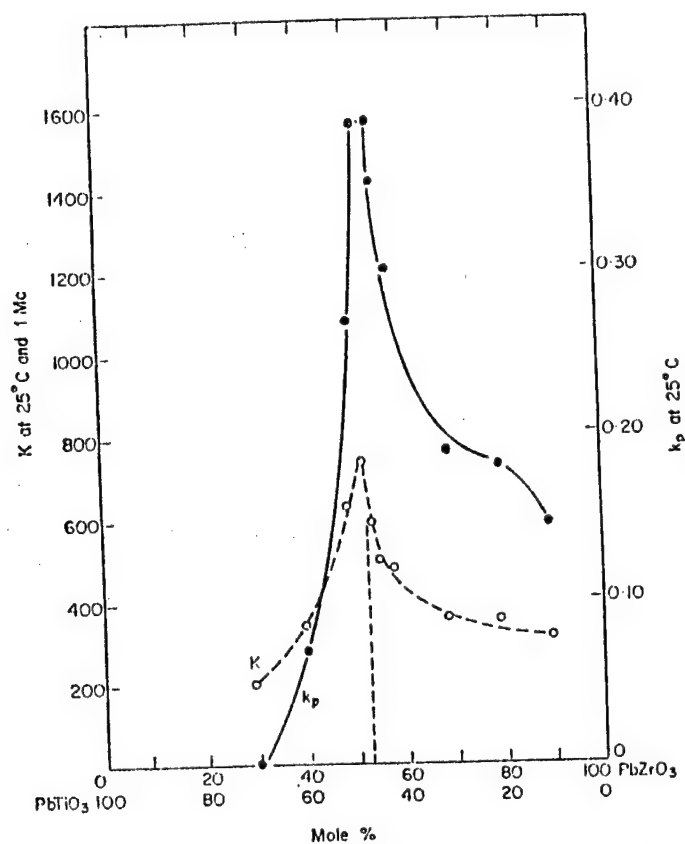
Dielectric constant and planar coupling versus composition for the system PbTiO₃-PbZrO₃.[14]

$$\Delta G = \alpha_1 [P_1^2 + P_2^2 + P_3^2] + \alpha_{11} [P_1^4 + P_2^4 + P_3^4]$$

$$+ \alpha_{12} [P_1^2 P_2^2 + P_2^2 P_3^2 + P_3^2 P_1^2] + \alpha_{111}[P_1^6 + P_2^6 + P_3^6]$$

$$+ \alpha_{112} [P_1^4 (P_2^2 + P_3^2) + P_2^4 (P_1^2 + P_3^2) + P_3^4 (P_1^2 + P_2^2)]$$

$$+ \alpha_{123} P_1^2 P_2^2 P_3^2 + \sigma_1 [p_1^2 + p_2^2 + p_3^2] + \sigma_{11} [p_1^4 + p_2^4 + p_3^4]$$

$$+ \sigma_{12} [p_1^2 p_2^2 + p_2^2 p_3^2 + p_3^2 p_1^2] + \sigma_{111} [p_1^6 + p_2^6 + p_3^6]$$

$$+ \sigma_{112} [p_1^4 (p_2^2 + p_3^2) + p_2^4 (p_1^2 + p_3^2) + p_3^4 (p_1^2 + p_2^2)]$$

$$+ \sigma_{123} p_1^2 p_2^2 p_3^2 + \mu_{11} [P_1^2 p_1^2 + P_2^2 p_2^2 + P_3^2 p_3^2]$$

$$+ \mu_{12} [P_1^2 (p_2^2 + p_3^2) + P_2^2 (p_1^2 + p_3^2) + P_3^2 (p_1^2 + p_2^2)]$$

$$+ \mu_{44} [P_1 P_2 p_1 p_2 + P_2 P_3 p_2 p_3 + P_3 P_1 p_3 p_1] + \beta_1 [\theta_1^2 + \theta_2^2 + \theta_3^2]$$

$$+ \beta_{11} [\theta_1^4 + \theta_2^4 + \theta_3^4] + \gamma_{11} [P_1^2 \theta_1^2 + P_2^2 \theta_2^2 + P_3^2 \theta_3^2]$$

$$+ \gamma_{12} [P_1^2 (\theta_1^2 + \theta_2^2) + P_2^2 (\theta_1^2 + \theta_3^2) + P_3^2 (\theta_1^2 + \theta_2^2)]$$

$$+ \gamma_{44} [P_1 P_2 \theta_1 \theta_2 + P_2 P_3 \theta_2 \theta_3 + P_3 P_1 \theta_3 \theta_1]$$

$$- 1/2 S_{11}[X_1^2 + X_2^2 + X_3^2] - S_{12} [X_1 X_2 + X_2 X_3 + X_3 X_1]$$

$$- 1/2 S_{44} [X_4^2 + X_6^2 + X_6^2] - Q_{11} [X_1 P_1^2 + X_2 P_2^2 + X_3 P_3^2]$$

$$- Q_{12} [X_1 (P_2^2 + P_3^2) + X_2 (P_1^2 + P_3^2) + X_3 (P_1^2 + P_2^2)]$$

$$- Q_{44} [X_4 P_2 P_3 + X_5 P_1 P_3 + X_6 P_1 P_2] - Z_{11} [X_1 p_1^2 + X_2 p_2^2 + X_3 p_3^2]$$

$$- Z_{12} [X_1 (p_2^2 + p_3^2) + X_2 (p_1^2 + p_3^2) + X_3 (p_1^2 + p_2^2)]$$

$$- Z_{44} [X_4 p_2 p_3 + X_5 p_1 p_3 + X_6 p_1 p_2] - R_{11} [X_1 \theta_1^2 + X_2 \theta_2^2 + X_3 \theta_3^2]$$

$$- R_{12} [X_1 (\theta_2^2 + \theta_3^2) + X_2 (\theta_1^2 + \theta_3^2) + X_3 (\theta_1^2 + \theta_2^2)]$$

$$- R_{44} [X_4 \theta_2 \theta_3 + X_5 \theta_1 \theta_3 + X_6 \theta_1 \theta_2] \qquad (1)$$

The coefficients of this energy function are defined in Table I. The energy function includes all possible ferroelectric and antiferroelectric polarization terms up to the sixth order, tilt angle terms up to the first fourth order term, and only the first order coupling terms.

a_i, a_{ij}, a_{ijk}	ferroelectric dielectric stiffness at constant stress
a_i, a_{ij}, a_{ijk}	antiferroelectric dielectric stiffness at constant stress
β_{ij}	coupling between the ferroelectric and antiferroelectric polarizations
B_i, B_{ij}	octahedral torsion coefficients
γ_{ij}	coupling between the ferroelectric polarization and tilt angle
s_{ij}	elastic compliances at constant polarization
Q_{ij}	electrostrictive coupling between the ferroelectric polarization and stress
Z_{ij}	electrostrictive coupling between the antiferroelectric polarization and stress
R_{ij}	rotostrictive coupling between the tilt angle and stress

IV. SOLUTIONS TO THE ENERGY FUNCTION

Considering zero stress conditions the following solutions to the energy function (Equation 1) are of interest in the PZT system:

Paraelectric Cubic (P_C)

$$P_1 = P_2 = P_3 = 0, \qquad p_1 = p_2 = p_3 = 0, \qquad \theta_1 = \theta_2 = \theta_3 = 0 \qquad (2)$$

Ferroelectric Tetragonal (F_T)

$$P_1 = P_2 = 0, \qquad P_3^2 \neq 0, \qquad p_1 = p_2 = p_3 = 0, \qquad \theta_1 = \theta_2 = \theta_3 = 0 \qquad (3)$$

Ferroelectric Orthorhombic (F_O)

$$P_1 = 0, \qquad P_3^2 = P_1^2 \neq 0, \qquad p_1 = p_2 = p_3 = 0, \qquad \theta_1 = \theta_2 = \theta_3 = 0 \qquad (4)$$

Ferroelectric High-temperature Rhombohedral ($F_{R(HT)}$)

$$P_1^2 = P_3^2 = P_1^2 \neq 0, \qquad p_1 = p_2 = p_3 = 0, \qquad \theta_1 = \theta_2 = \theta_3 = 0 \qquad (5)$$

Ferroelectric Low-temperature Rhombohedral ($F_{R(LT)}$)

$$P_1^2 = P_3^2 = P_1^2 \neq 0, \qquad p_1 = p_2 = p_3 = 0, \qquad \theta_1^2 = \theta_2^2 = \theta_3^2 \neq 0 \qquad (6)$$

Antiferroelectric Orthorhombic (A_O)

$$P_1 = P_2 = P_3 = 0, \qquad p_1 = 0, \qquad p_2^2 = p_3^2 \neq 0, \qquad \theta_1 = \theta_2 = \theta_3 = 0 \qquad (7)$$

All of these solutions, except for the ferroelectric orthorhombic solution, are stable in the PZT system. The ferroelectric orthorhombic solution was also included here, because the coefficients necessary to calculate the energy of this phase can be determined. An independent check of the calculated coefficients can then be made by confirming that this phase is metastable across the PZT system.
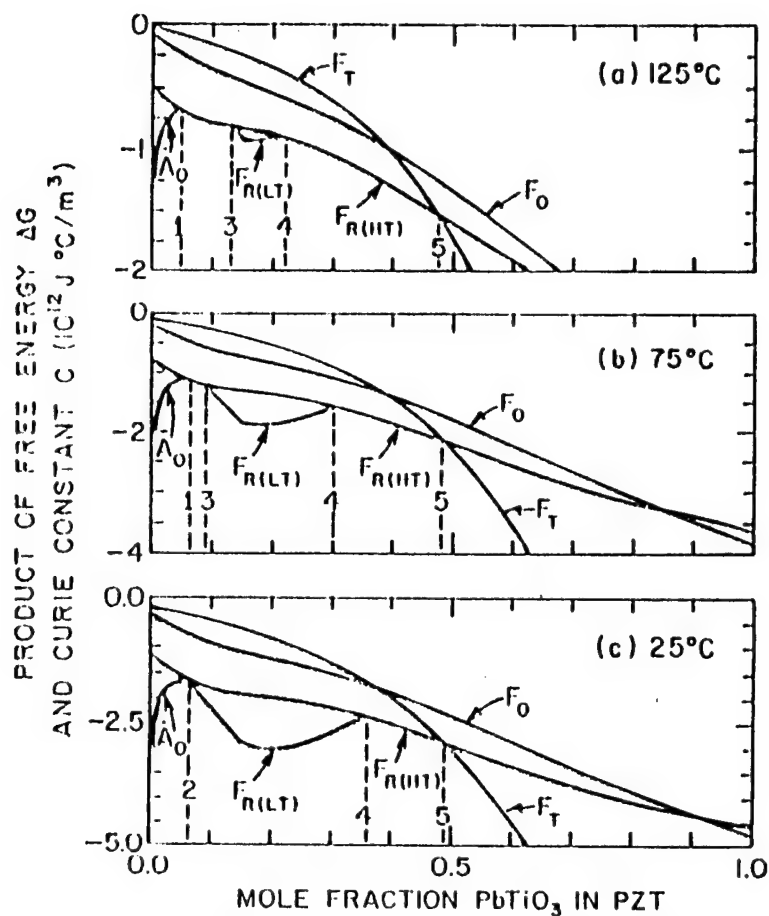
The product of the free energy ΔG and Curie constant plotted versus composition for the different solutions of the energy function.
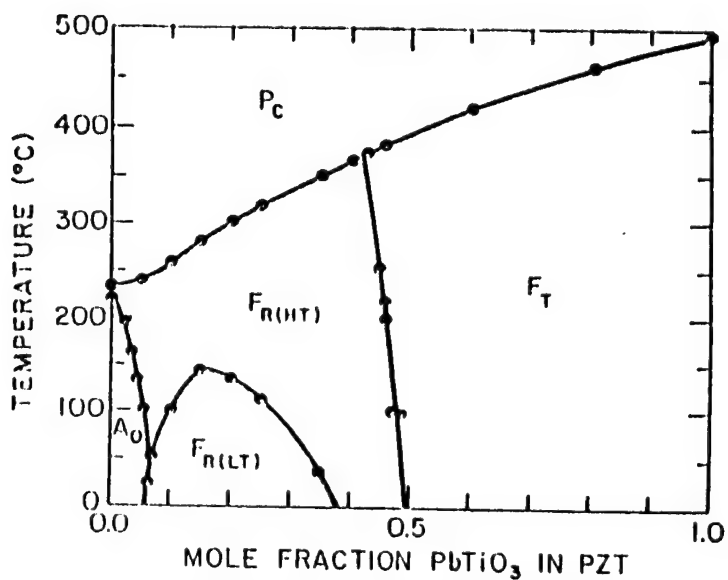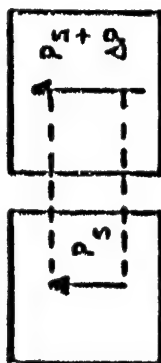

Superposition of the theoretical and experimental phase diagrams. The data points are from the experimental phase diagram.[6] The solid curves are the theoretical calculations.

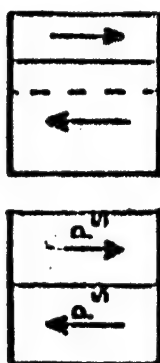## Polarization Mechanisms in Piezoceramics

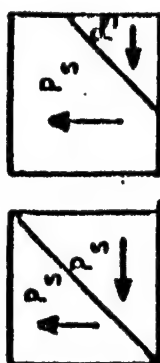(a) High Field

(1) Intrinsic Single Domain Polarizability — α_I

(2) 180° Domain Wall Motion — $\alpha_{D(180)}$
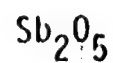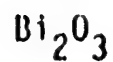
(3) Ferroelastic Wall Motion — $\alpha_{D(\theta)}$

(4) Ferroelectric Phase Change — α_{FE}

LOWER LEVEL MODIFIERS (0 to 10 MOLE %)

'Donor' Additives	'Acceptor' Additives
Nb_2O_5 or $PbNb_2O_6$	Fe_2O_3
Ta_2O_5 or $PbTa_2O_6$	Al_2O_3
WO_3	Cr_2O_3
Bi_2O_3	MnO_2
Sb_2O_5	MgO
La_2O_3	NiO

$$V_3O_8$$
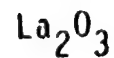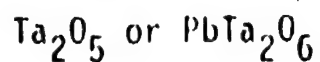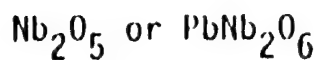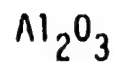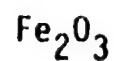
Other Low Level Additives:

Na_2O, K_2O, Ga_2O_3, In_2O_3, IrO_2, ThO_2
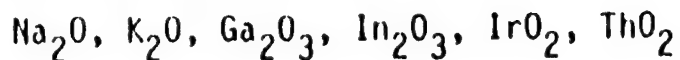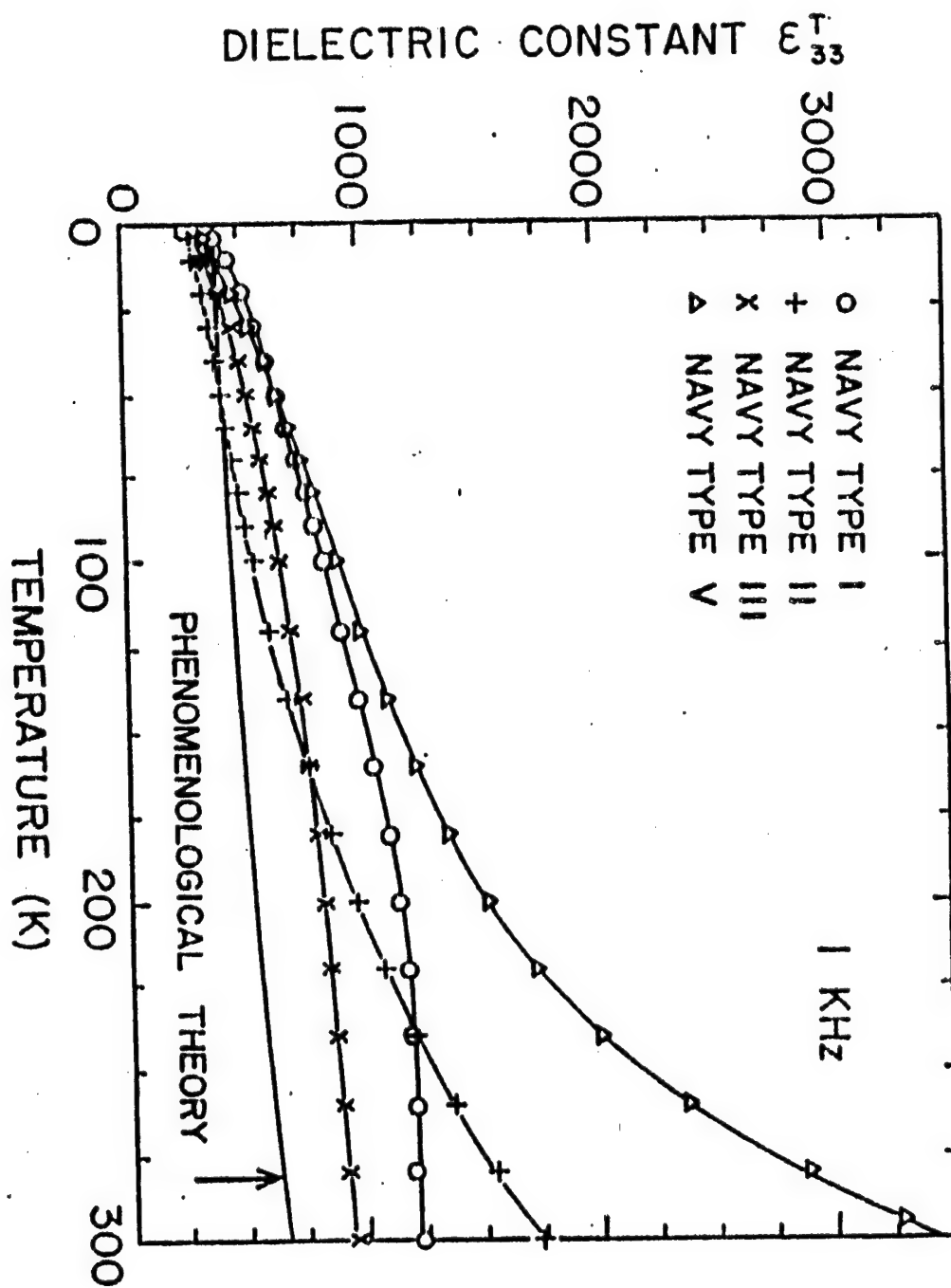
ELECTROSTRICTIVE ACTUATORS

Direct Electrical Control of shape (strain) in an insulating solid.
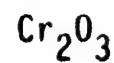
Electrostriction.

$$x_{kl} = M_{ijkl} \, E_i E_j$$

$$\frac{l_1 - l_0}{l_0} = M_{1111} \, E_1^2$$
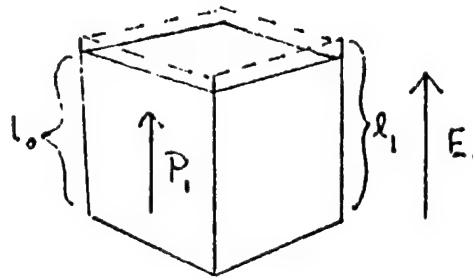
$$x_{kl} = Q_{ijkl} \, P_i P_0$$

M values widely scattered in different insulators.

Q values – much more limited range. Systematic change with elastic behavior.

Controlling dimensions in an electrostrictive requires control of polarization.
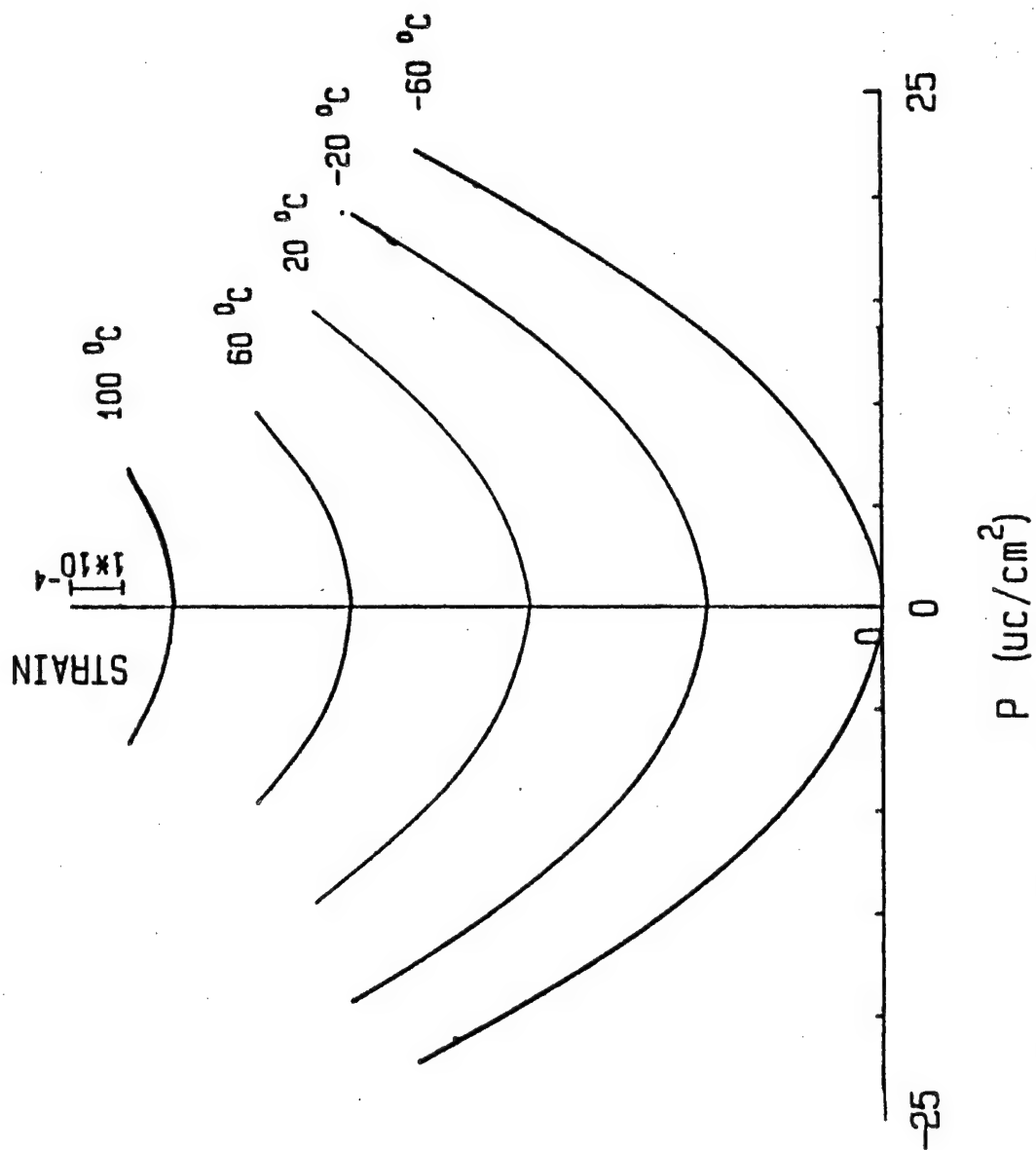
Polarization dependence of longitudinal strain at
selected temperatures for Pb $(Mg_{1/2}Nb_{1/3})O_3$ ceramics
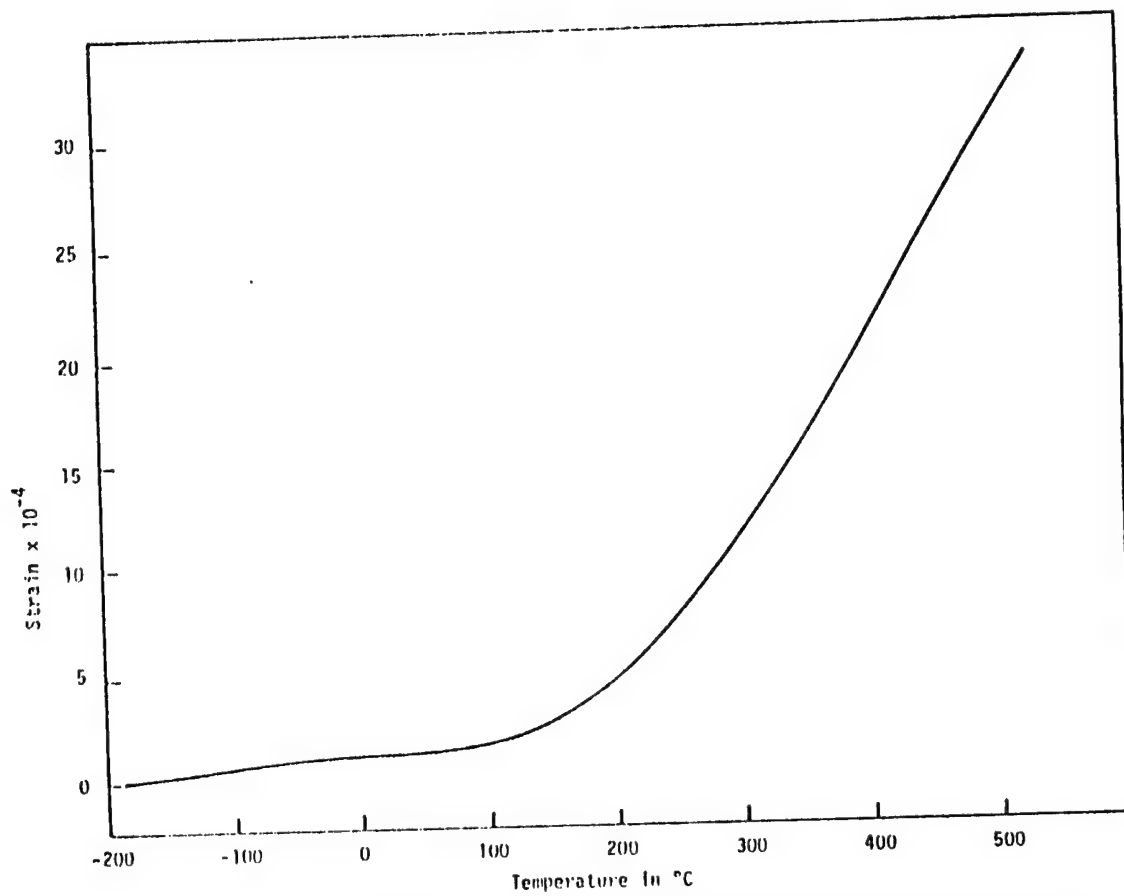
Thermal strain of polycrystalline 0.9 PMN 0.1 PT ceramic. The linear thermal expansion is about 10^{-5} C^{-1} at 400°C and less than 10^{-6} C^{-1} at room temperature.

PZT $(E = 16 \times 10^5 \ (V/m))$ ⟸ Piezoelectric

0.65 PMN-0.35 PT
$(E = 8.4 \times 10^5 \ (V/m))$ ⟸ Electrostrictor

$E = 15 \times 10^3 \ (V/m)$

limiting

What is the load line?

How does it change with frequency; fatigue?

limit with 5,000 lbs/in²

$10 \times 10^3 \ (V/m)$

$0 \ (V/m)$

$-2 \ (V/m)$

$X_3 \times 10^6 \ [N/m^2]$

$x_3 \ (\times 10^{-4})$

1 mil/inch

27
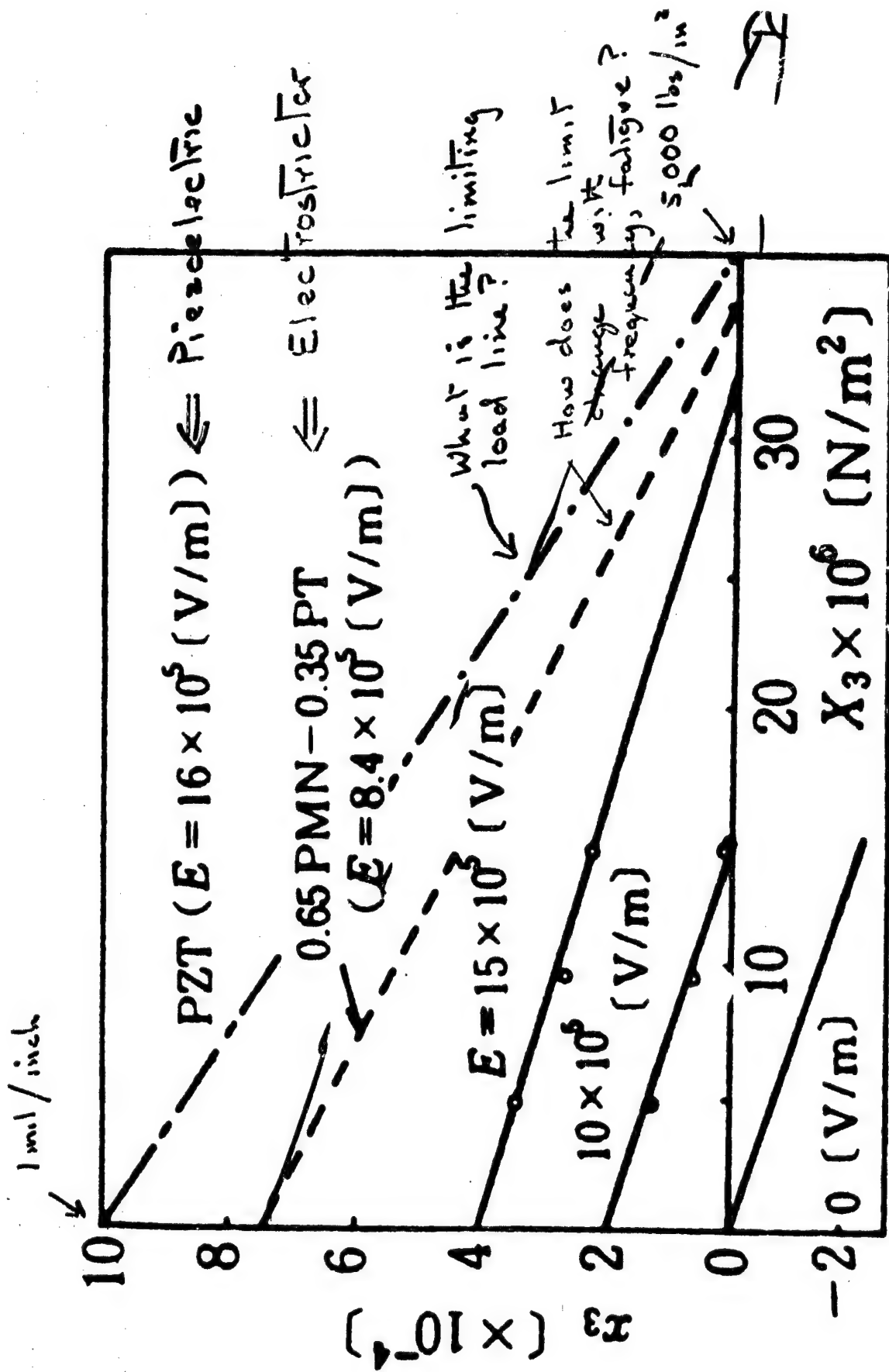
COMPOSITE ELECTROCERAMICS

KEY ELEMENTS IN DESIGN OF COMPOSITES.

* CONNECTIVITY. *- much already accomplished*

   Mode of self interconnection for the individual phases: controls, fluxes, and fields in the composite.

* SYMMETRY OF THE ARRANGEMENT. *- for the future*

   Curie Group macro-symmetries can modify property tensors in highly desirable ways.

* SCALE. *- very active at present.*

   Mode of averaging depends on wavelength of excitation vs. scale of composite. Unusual resonances can occur when λ and $\bar{d}$ are comparable.

SCHEMATIC DIAGRAM OF DIFFERENT COMPOSITES

SANDWICH COMPOSITE (1-3)

SANDWICH COMPOSITE (3-3)

LADDER STRUCTURE (3-3)

LADDER STRUCTURE (3-3)

REPLAMIN (3-3) COMPOSITE

BURPS COMPOSITE (3-3)

GLASS-CERAMIC COMPOSITE MODEL

PZT SPHERES IN A POLYMER (1-3)

DICED 1-3 COMPOSITE
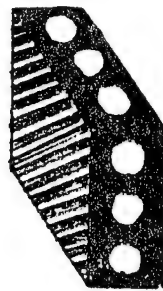
PERFORATED COMPOSITE (3-2)

TRANSVERSE REINFORCEMENT (1-2-3-0)

PZT RODS IN A POLYMER (1-3)

PERFORATED COMPOSITE (3-1)

PARTICLES IN A POLYMER (0.3)

HONEYCOMB COMPOSITE PARALLEL POLING (1-3)

HONEYCOMB COMPOSITE TRANSVERSE POLING (3-1)

PVDF COMPOSITE MODEL

29
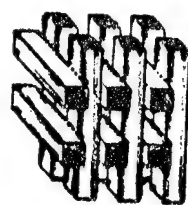
TENSOR ENGINEERING IN ACTIVE COMPOSITES

NAVY HYDROPHONE

Up to 1975   Material lead zirconate titanate piezoelectric ceramic PZT

Power figure of merit $d_h g_h$

Product of hydrostatic voltage × hydrostatic charge

$d_h g_h$ In tensor form $\rightarrow \dfrac{(d_{333} + 2d_{311})^2}{\epsilon_{33}}$

$$d_h g_h \sim 100 \cdot 10^{-15} \, M^2/\text{Newton}$$

PROBLEM $d_{333} \cong -2d_{311}$ ϵ_{33} very large

COMPOSITE SOLUTION

TRANSVERSE REINFORCEMENT
(1 – 2 – 3 – 0)
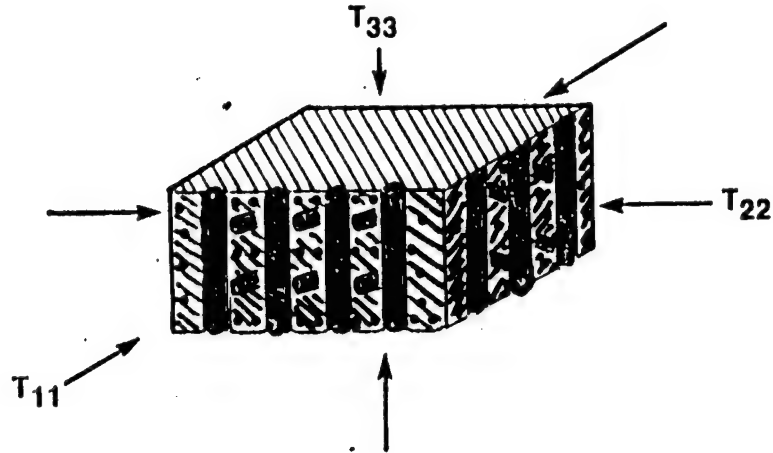
$$p = \begin{vmatrix} -T_{11} & 0 & 0 \\ 0 & -T_{22} & 0 \\ 0 & 0 & -T_{33} \end{vmatrix}$$

$\left.\begin{matrix} \\ \\ \end{matrix}\right\}$ Taken up on transverse reinforcement

— Enforced on PZT
Polymer acts like a tent

ϵ_{33} much reduced by the polymer
Composite 10 v/o PZT 90% rubber

$$d_h g_h \cong 150,000 \cdot 10^{-15} \, M^2/\text{Newton}$$
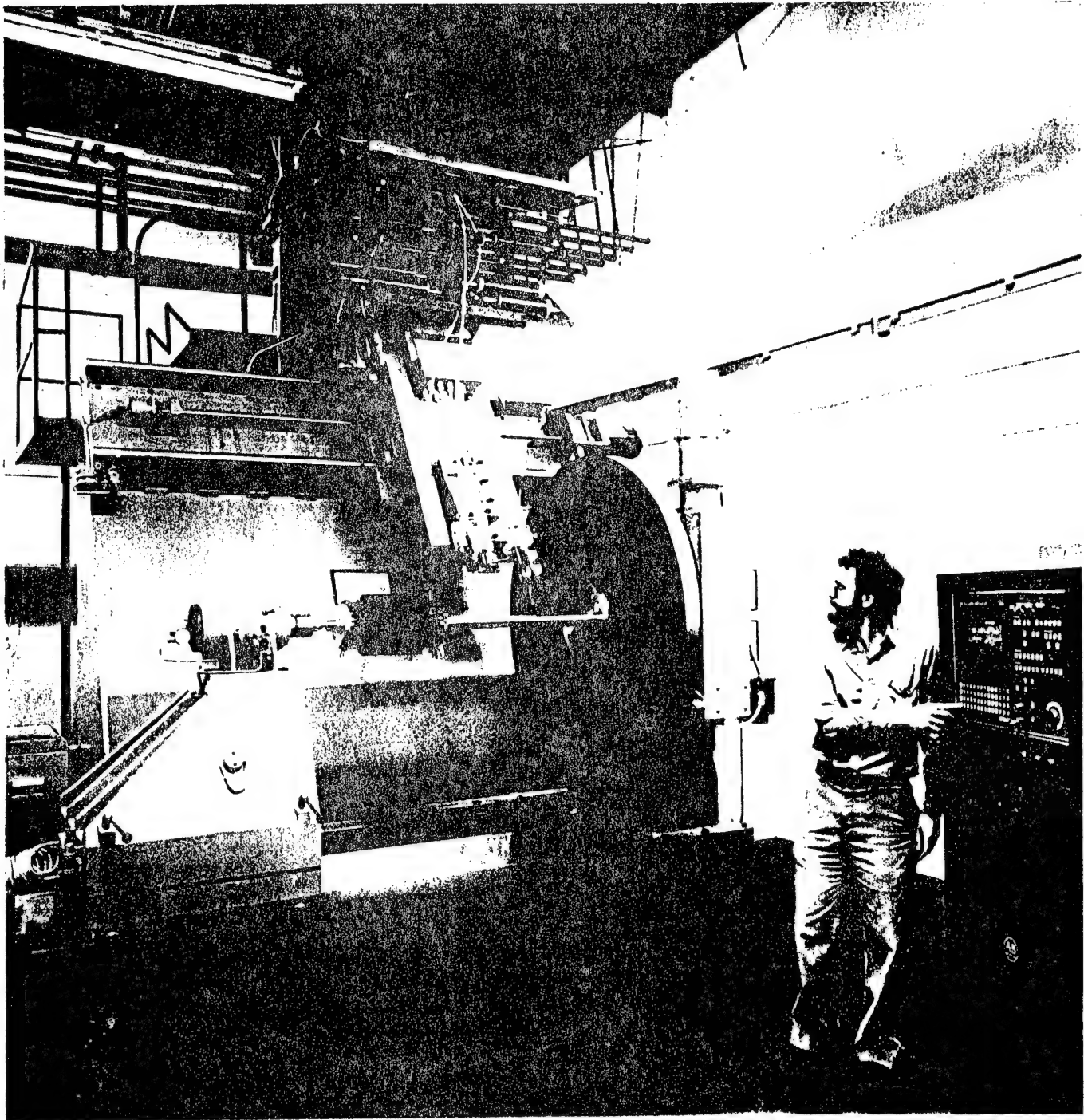
ULTRALOOM^{TM}

PIEZOELECTRIC
ROD POSITIONING AND INSERTION

Thickness mode
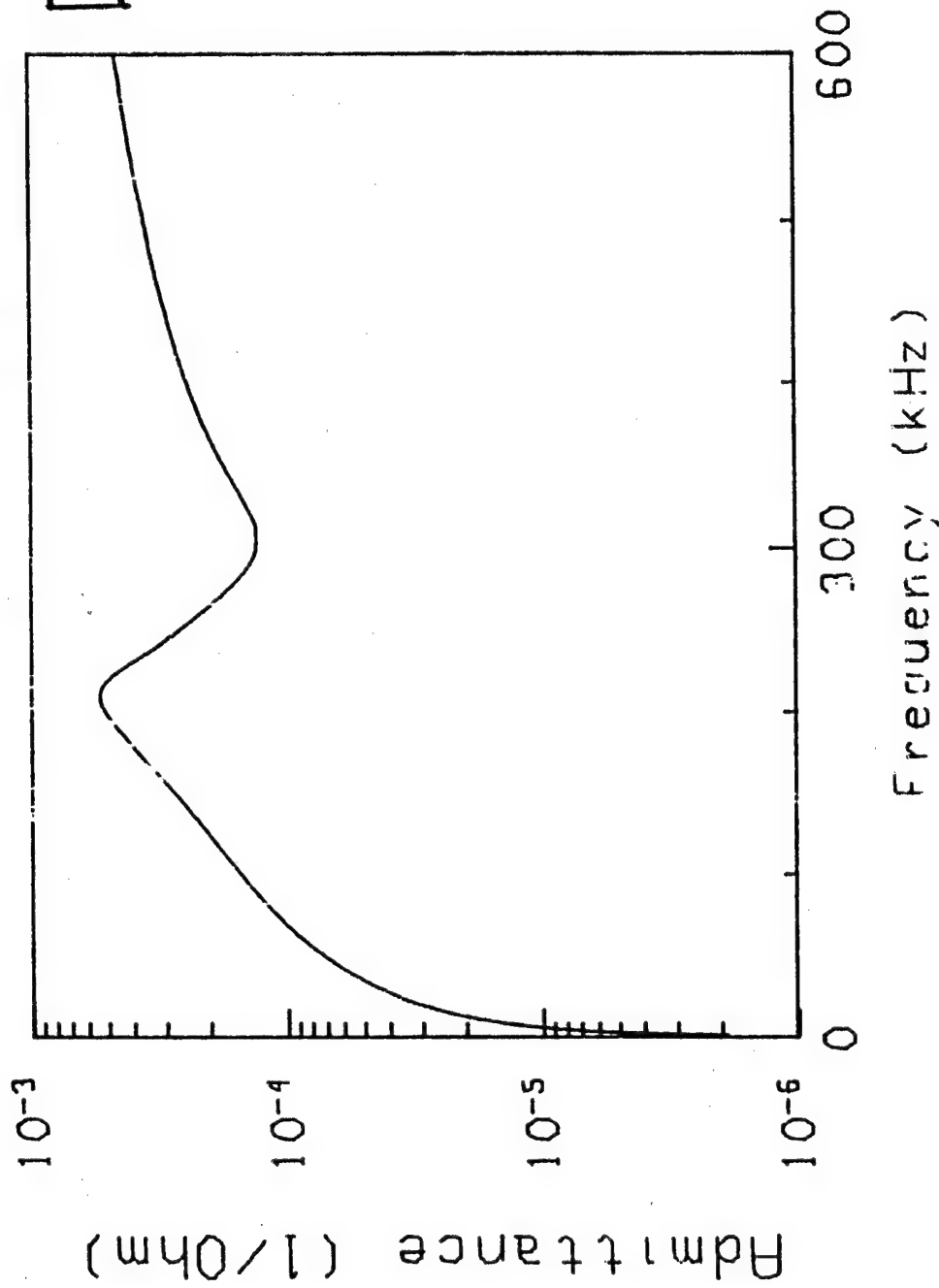
$K_T = 70\%$

Rods:

PZT - 5H
square rods 1x1 mm²
spacing: 4 mm
thickness: 5.3 mm
5 vol.%

Reinforcement:

glass fibers
5 vol.%

Polymer

flexibilized epoxy

Admittance (1/Ohm)

10^{-3}
10^{-4}
10^{-5}
10^{-6}

Frequency (kHz)

0
300
600

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TECHNICAL PRESENTATION

"Progress in Intelligent Structures"

or

"Here's the Beef, Dan"

BY

Dr. Edward F. Crawley
Space Engineering Research Center

Comparison of Actuation Strain Materials

	PZT G-1195	PVDF	PMN-BA	TERFANOL DZ	NITINOL
Actuation Mechanism	piezoceramic	piezo film	electrostrictor	magnetostrictor	shape alloy
Λ max (μ strain)	1300	230 dc / 690 ac	1300	>2000	80000 dc / 20000 ac
E (lb/in²) x10-6	9.14	0.29	17.5	7.0	4.35 (m) 12.9 (a)
ε max (μ strain)*	448	11	653	575	8520 (a)
T max (oC)	360	80-120	high	380	45
linearity	good	good	fair	fair	poor
hysteresis	10%	>10%	<1%	2%	5%
temp sens. (%/oC)	.05	.8	.9	high	-
bandwidth	high	high	"high"	moderate	low

* for a sheet of actuator bonded to aluminum beam (t_s/t_a=10) in bending assuming ac value of Λ

(m) = martensite   (a) = austenite

EXPERIMENTATION: PLATE ARTICLES

- Cantilever Plate Configuration: Actuators Cover 71% of Plate

Cross Section A-A

5.1 cm
2.5 cm
15.2 cm

Power Bus Cross Section

0.4 mm
5.1 mm

29.2 cm

5.1 cm

Clamp

□ Piezoceramics
▦ Aluminum or G/E Substrate
▨ Strain Gage

▮ Power Bus
— Power Leads
---- Ground Leads
□ Copper Tape
▨ Insulating Tape

Test Specimen

Semi-Conductor Strain Gage (8)

Piezoceramic (32)

Accelerometers (8)
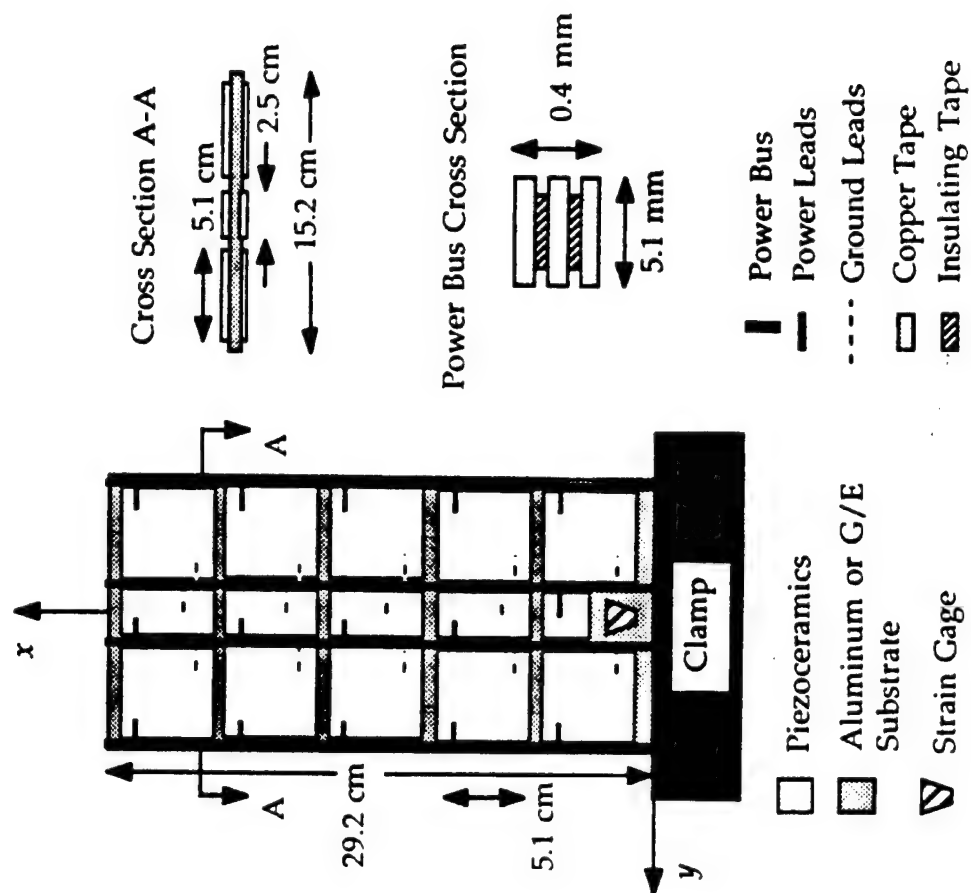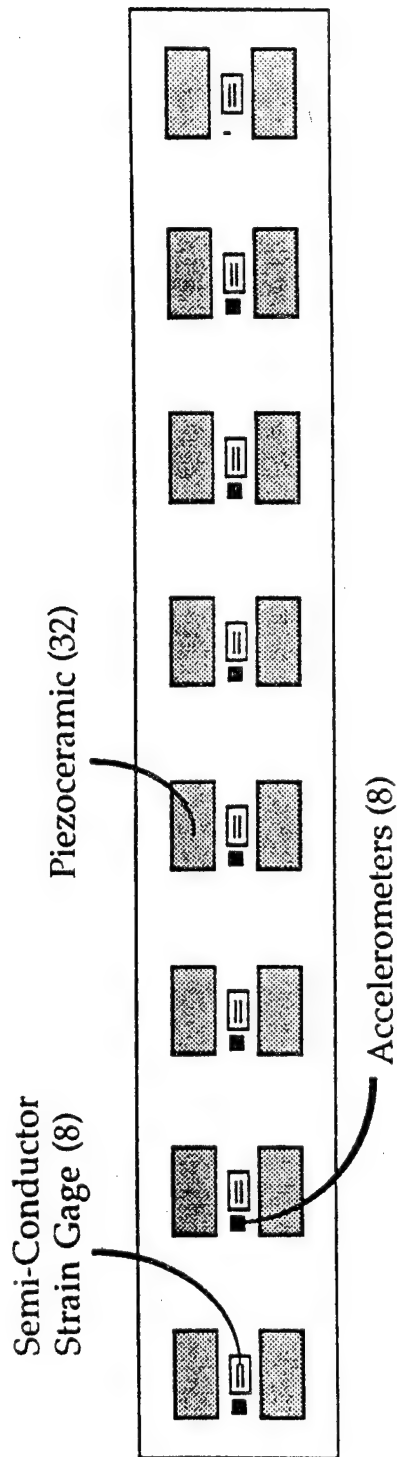
- 4 ft. by 6 in. 22 ply graphite/epoxy beam hung in a free-free configuration.

- $[0_2/90_7/0_2]_s$ layup with actuators embedded in the sixth and seventeenth plies.

- 32 piezoceramics arranged to form 8 actuator sets.

- Semi-conductor strain gage at each actuator location.

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Structural Shape Determination Objectives

Objective is to determine "optimal" type and number of sensors to allow accurate reconstruction of structural shape from discrete curvature measurements.

Issues considered include:

- Accuracy of predicted slope and displacement for various integration rules as a function of the number of gages.

- Feasibility of accurate static and dynamic mode shape determination using strain-averaging sensors.

- Frequency characteristics of a single sensor.

- Frequency characteristics of integrated shape measurement.

Examples of Single Sensor Characteristics

Shape	Advantages	Disadvantages
Sinc	Gives perfect rolloff with no phase lag.	Is of infinite extent in x. Has negative regions in x. Hard to manufacture and distribute.
Rectangle	Very simple shape. Can be distributed easily. Has no negative regions in x.	Only -20 db/decade rolloff. Has large negative regions in k.
Gauss	Has no negative regions in x or k. Has good rolloff (-300 db in 1st decade). Can be distributed.	Is of infinite extent in x.
Hanning[2]	Has no negative regions in x. Has good rolloff (-100 db/decade) Can be distributed.	Has small negative regions in k.
Gauss-Hanning	Has no negative regions in x or k. Has good rolloff (-60 db/decade) Can be distributed.	None.

Comparison of Fourier Transforms of Gauss (-), Hanning*Hanning (--) & Hanning*Gauss (.-) Windows

40
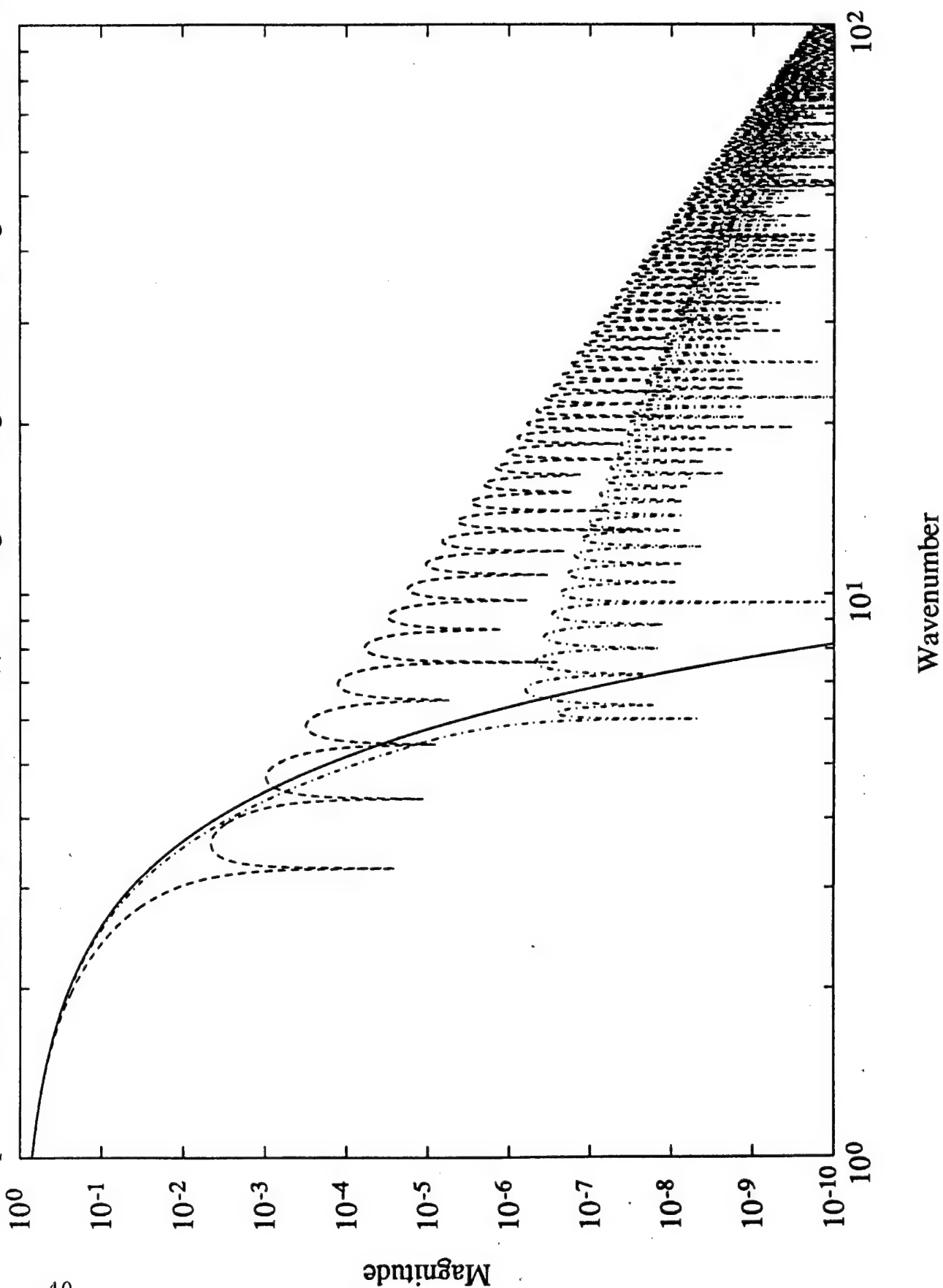
Displacement Error vs. Strain Gage Number
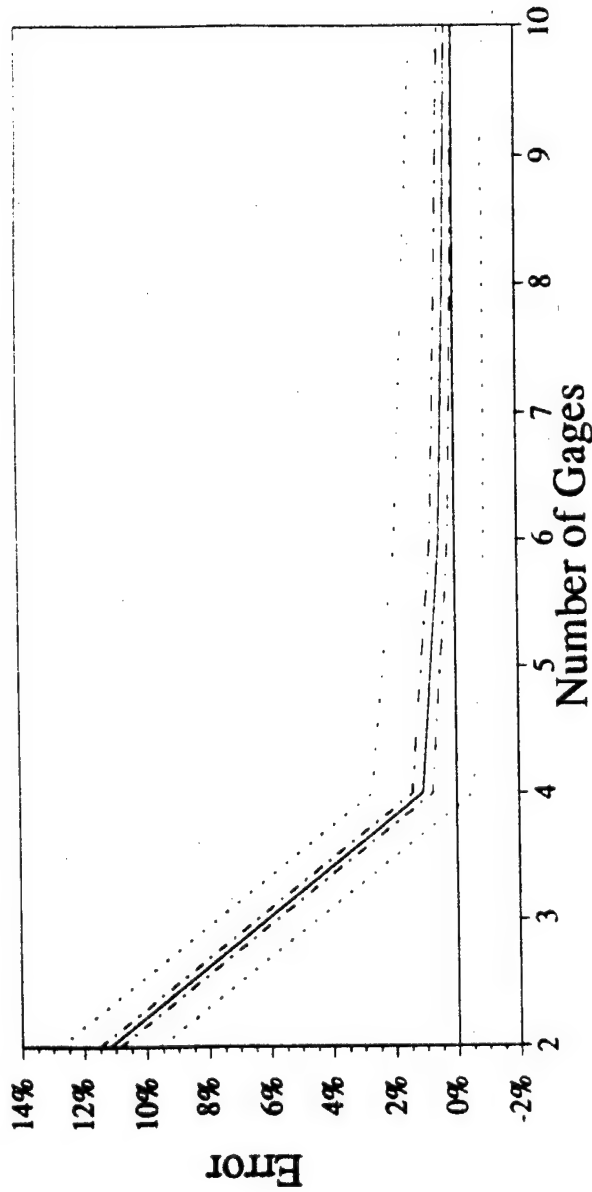
- Trapezoidal integration scheme with short strain gages, on a cantilevered beam.

- Results:
    - Solid line - integration errors only.
    - Dashed line - integration errors + 1% gage factor error + 0.2% placement error.
    - Dotted line - integration errors + 5% gage factor error + 1% placement error.

Embedding Devices within Composite Structures

Lines indicate
fiber direction

Device with leads to
be embedded

Ply with notch for leads

Plies with holes for device

Plies of graphite/epoxy
composite
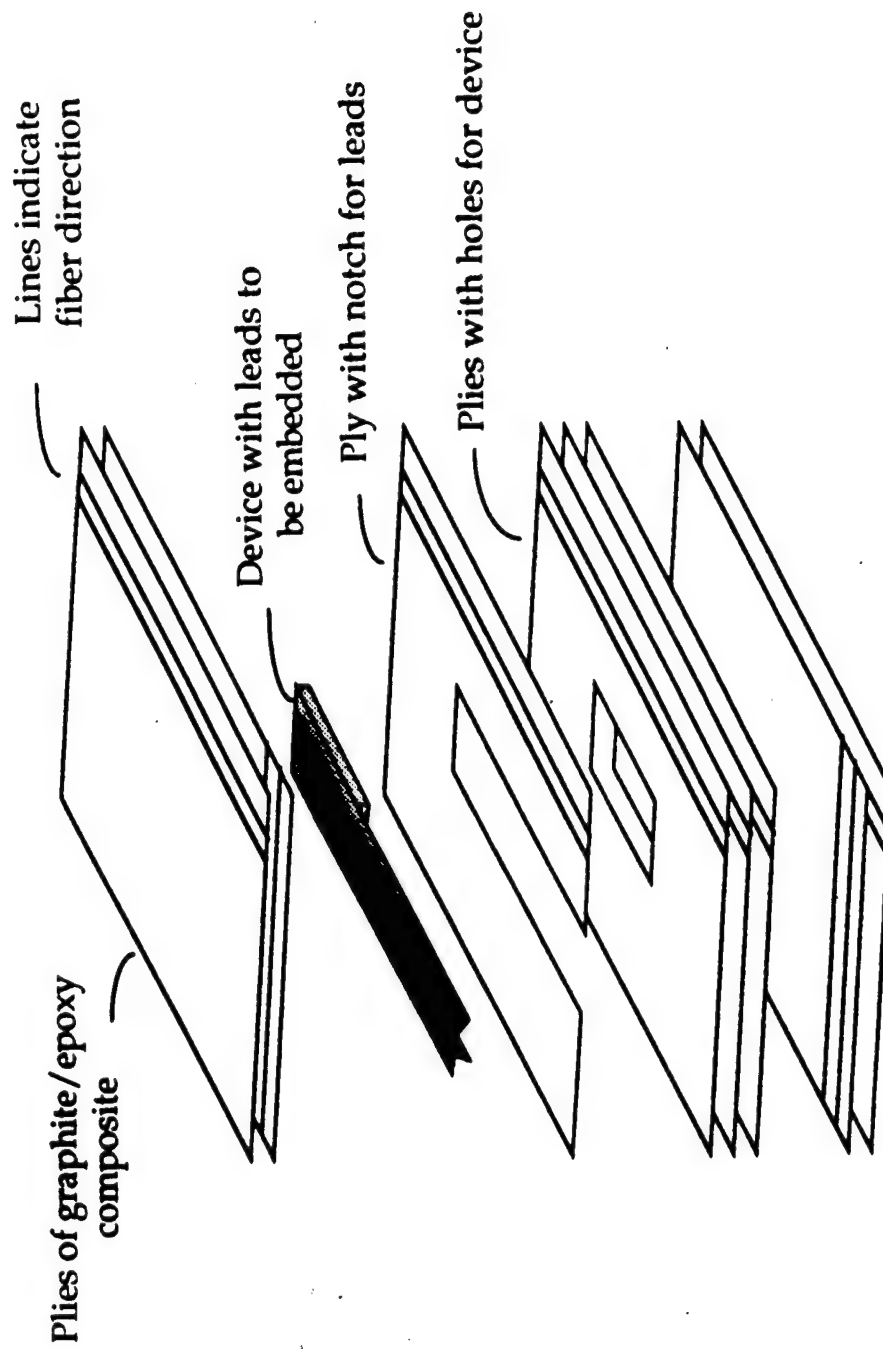
Static Tensile Load Test

Sensor 5 - RTV

Legend:
- long. far field
- side long.
- long. over chip

sensor failure at 149 ksi

strain (μstrain)

stress (psi)
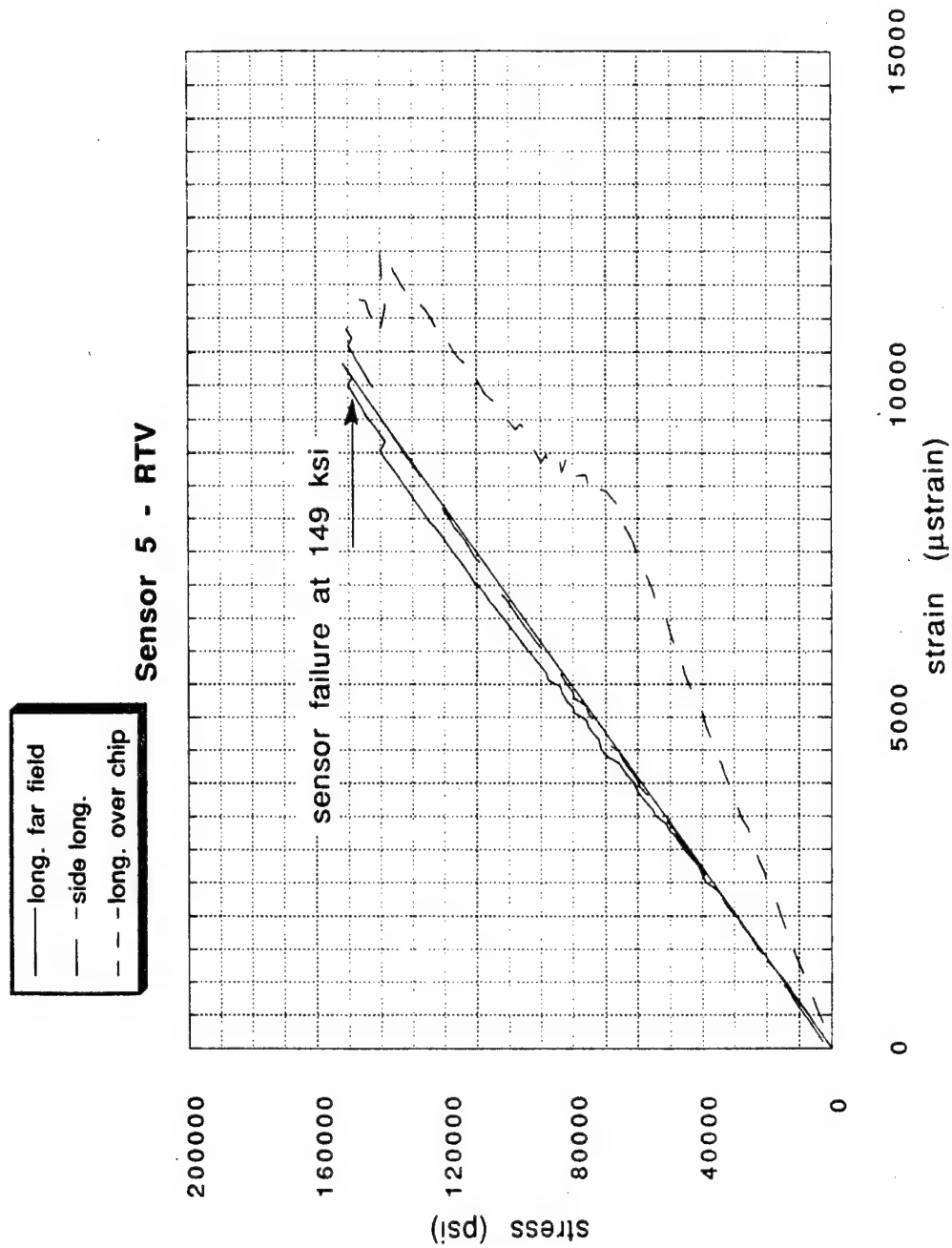
EXPERIMENTAL SET-UP BLOCK DIAGRAM

- Plant Model Developed from 20 Mode Ritz Analysis

- MIMO Compensators Designed using Reduced Order LQG or Optimal Projection Theory

- Sensor, Amplifier and Filter Dynamics Included in Model

- Compensators Implemented by a Real Time Digital Computer
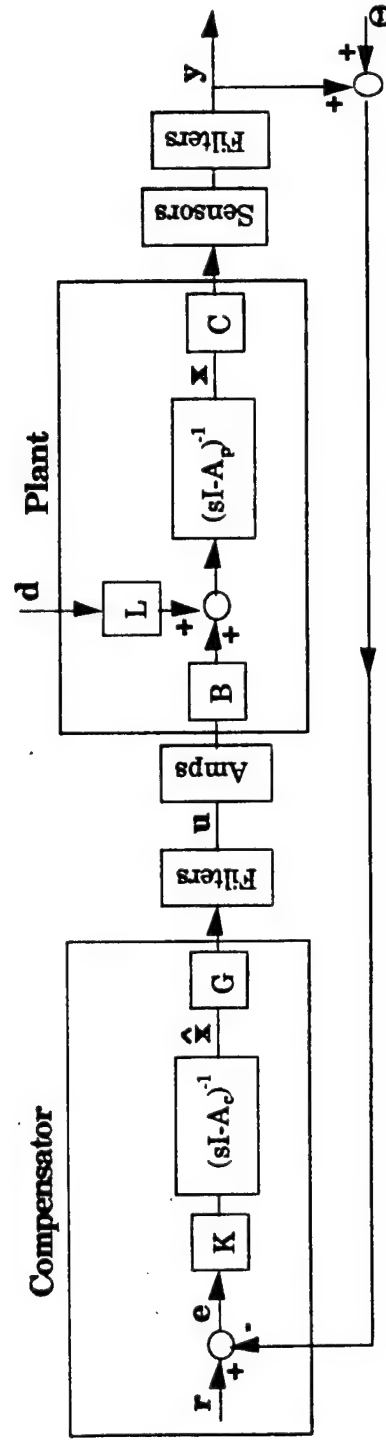
OPEN AND CLOSED LOOP FREQUENCY RESPONSE

Graphite/Epoxy Bend/Twist Coupled Specimen:

$\rho = 1e^{-2}$ $\qquad$ $\gamma = 3\%$
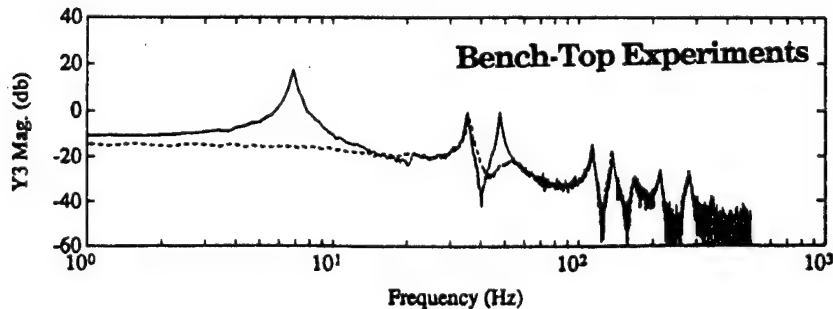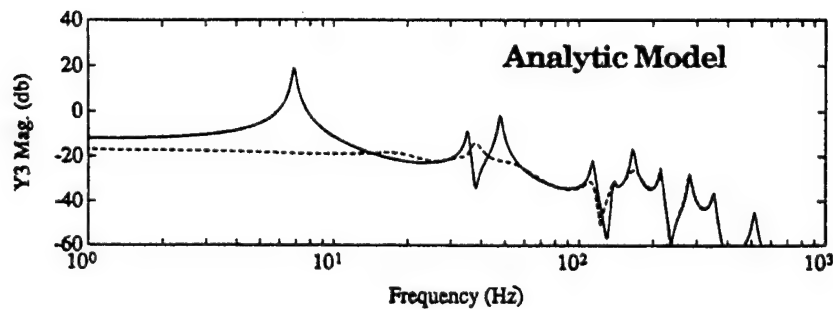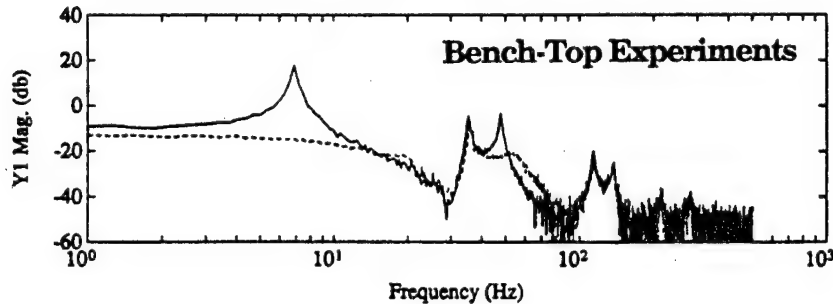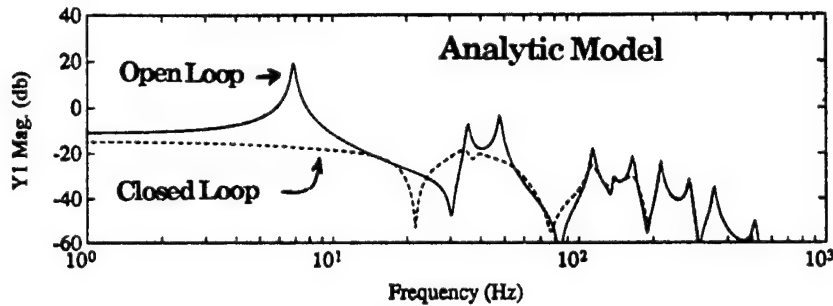
STATE COST VERSUS CONTROL COST

- Graphite/Epoxy Bend/Twist Coupled Specimen

- Reduced Order LQG Design: $\rho = 1e^{-2}$ Sensor Noise = 3%
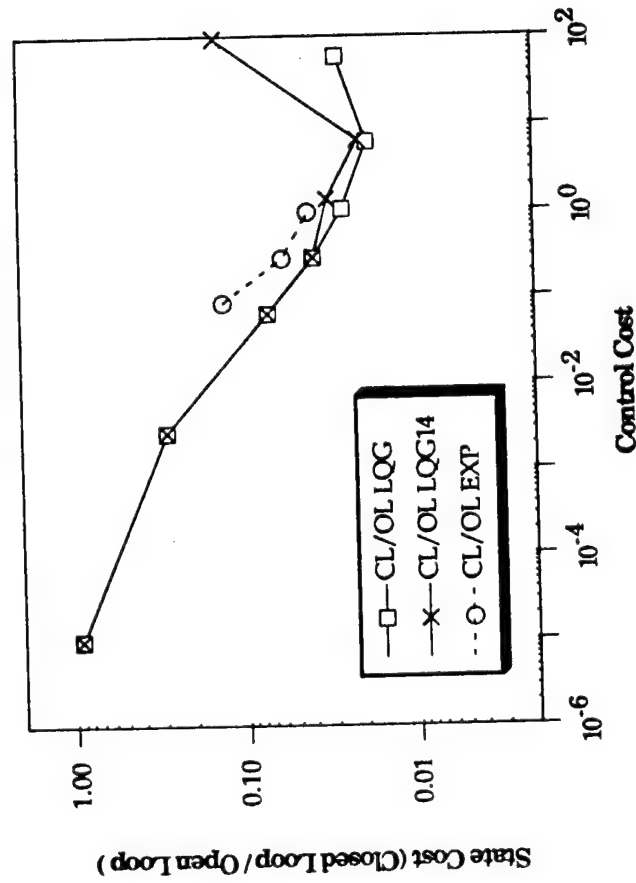
- State Cost Reduced by 96% (14 db RMS)
- Instabilities Caused by Actuator Saturation

Intel 87C196KB Block Diagram
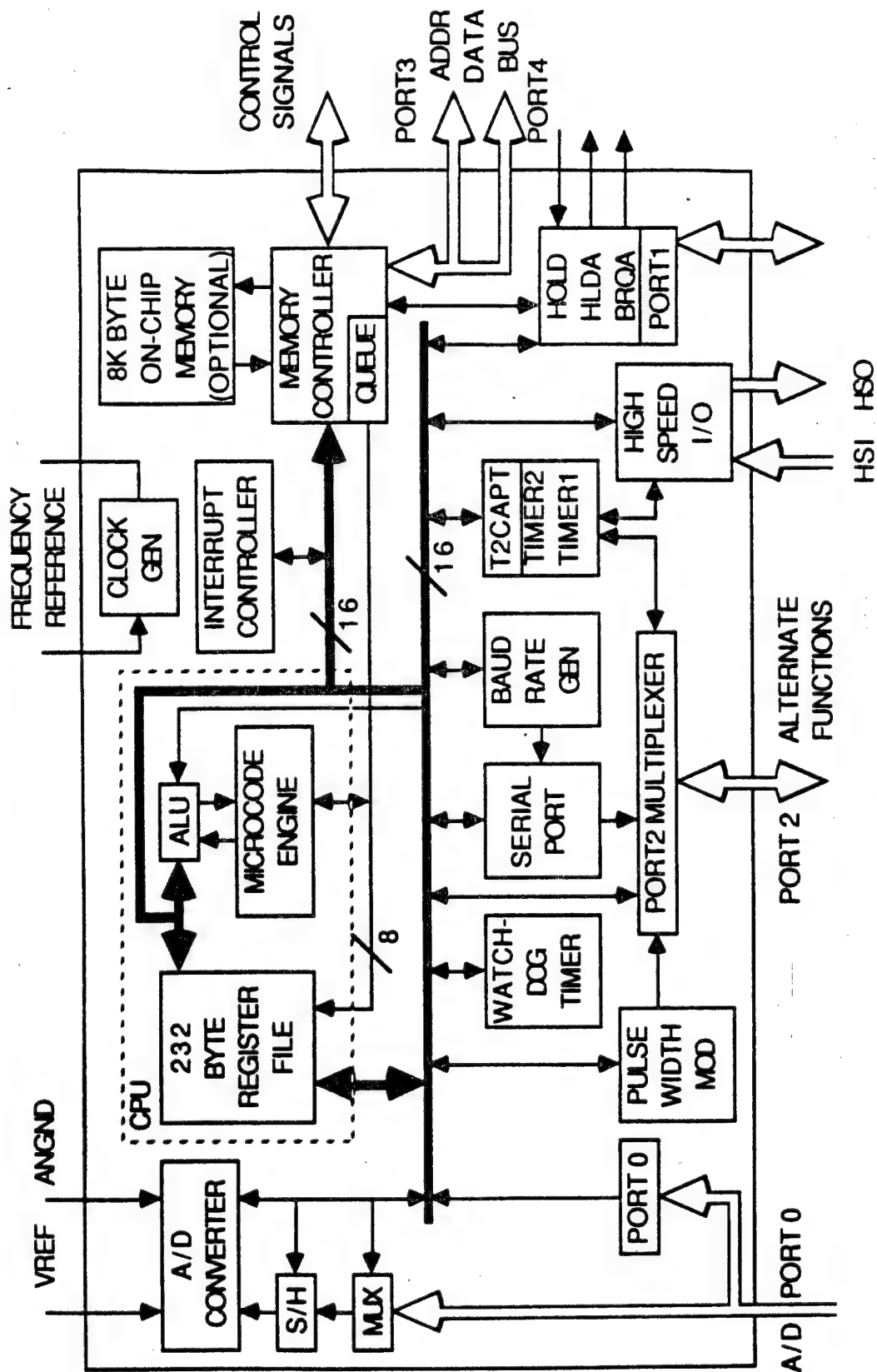
(from *INTEL 16-Bit Microcontroller Handbook*)

MIT Space Engineering Research Center

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Performance Achieved with Single-chip Microcomputer

Open loop disturbance response
Closed loop disturbance response

Magnitude of Disturbance Transfer Function
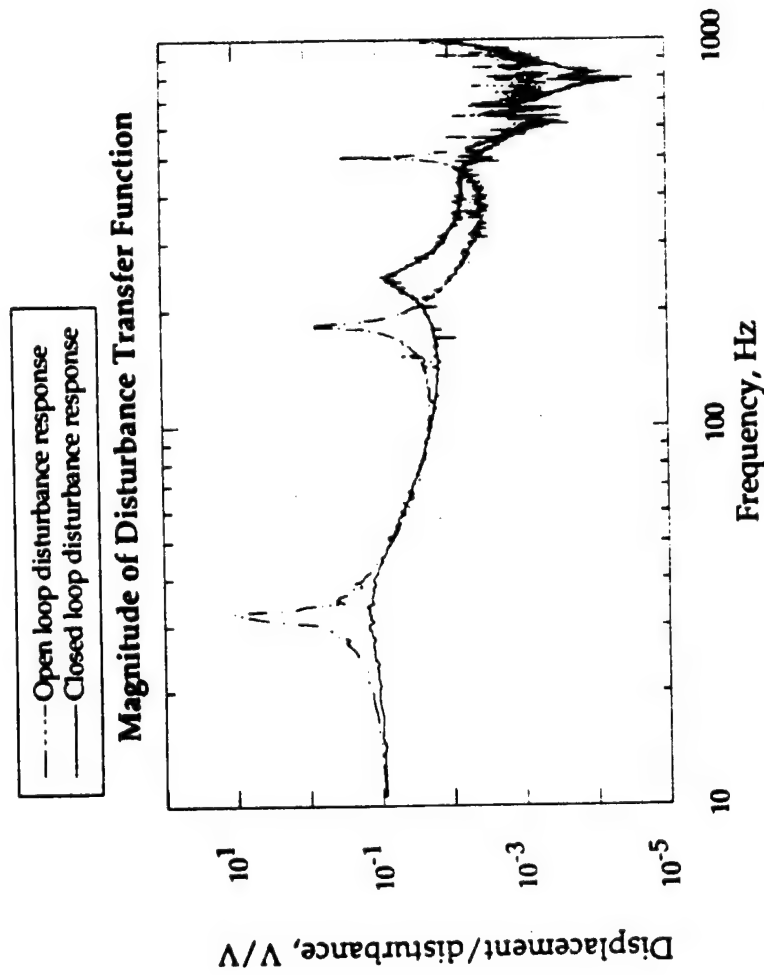
Increased damping 1st mode   0.36% OL   31% CL

2nd mode   0.15% OL   4% CL

MODIFIED TYPICAL SECTION

- **Geometry:**
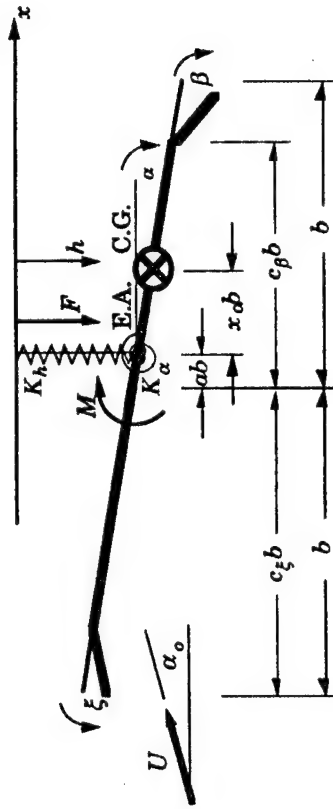
- **Assumptions:**

  – Plunge and Pitch Degrees of Freedom

  – Strain Actuator Inputs found from Equivalent Forces and Moments
    Produced at the 3/4 Span by Distributed Strain Actuators

  – Incompressible Steady Aerodynamics

  – Actuator Forces / Moments Act Instantaneously at the Elastic Axis

FULL STATE FEEDBACK (LQR) CONTROL

- Gains Found by Minimizing a Scalar Quadratic Cost Functional.

- State Penalties Normalized By Maximum Allowable Deflections Based on 1% Strain In the Modelled Wing.

- Control Penalties Normalized By Maximum Control Authority:

  - Strain Actuators: $\Lambda_{max} = 300\mu\varepsilon$ (maximum actuation strain)

  - Trailing Edge Flap: $\beta_{max} = 5^o$ (maximum flap deflection)

  - Leading Edge Flap: $\xi_{max} = 2.5^o$ (based on maximum hinge moment)

- State versus Control Weighting Varied:

  - High relative control weight $\Rightarrow$ "Expensive Control" $\Rightarrow$ Low Gain

  - Low relative control weight $\Rightarrow$ "Cheap Control" $\Rightarrow$ High Gain

STATE VERSUS CONTROL COST ANALYSIS

Design Point 2 (above flutter)

Key:

×	Bending Strain Control
o	Torsion Strain Control
▲	Trailing Edge Flap Control
– – –	Bending and Trailing Edge Flap Controls
·····	Torsion and Trailing Edge Flap Controls
——	Bending and Torsion Strain Controls
—•—	Bending, Torsion and Trailing Edge Flap Controls
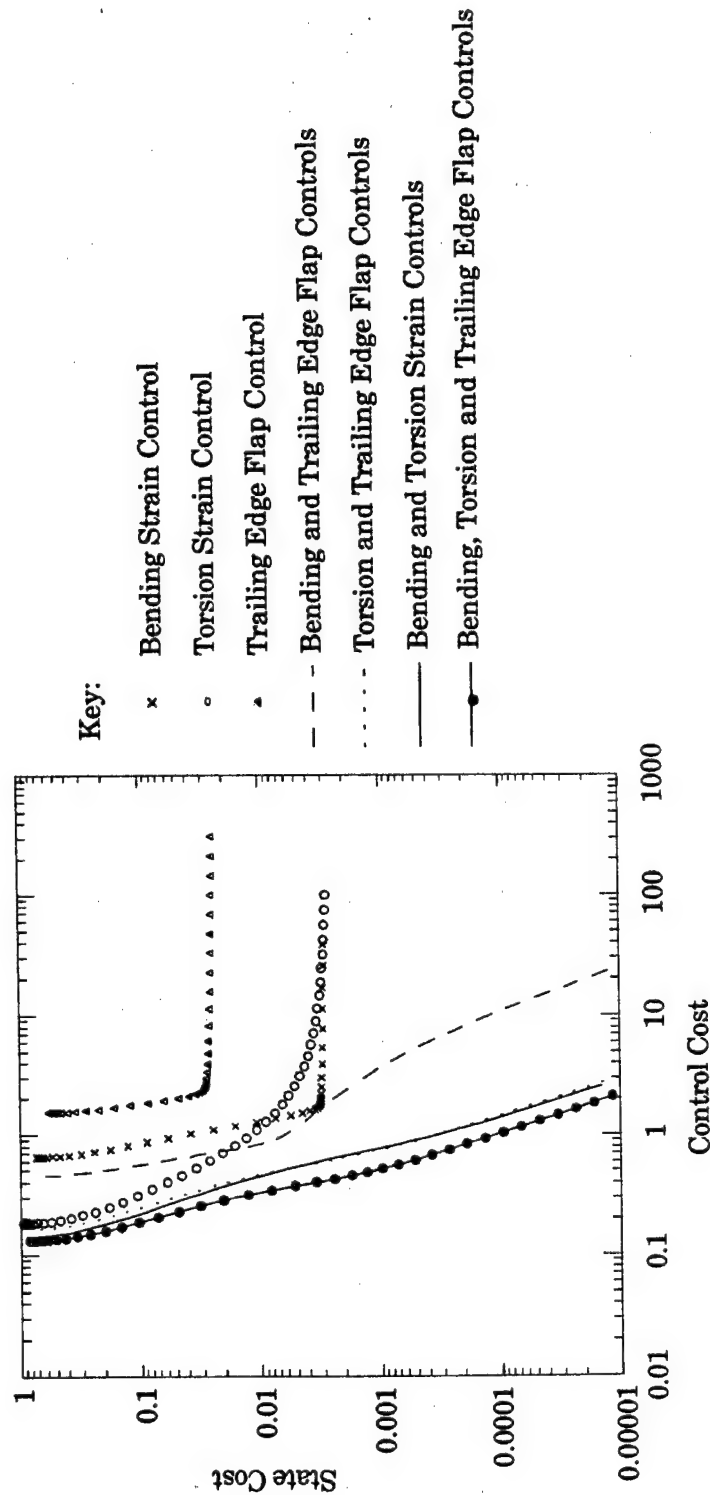
- **Similar Performance Results.**
  - Strain Actuators Provide Good Control Authority
  - Single Actuators Systems have Fundamental Limitation
- **Low Gain Asymptotic Limit due to Unstable System.**

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REMAINING OPEN ISSUES IN INTELLIGENT STRUCTURES:

6.0 Hue control, etc.

6.1 Better activator Material

Optimized sensors

Control algorithms which inherently take advantage of strain activation and sensing

Distributed Control

Power conditioning and switching

Structural Macro and Micro optimization

Signal and Power Circuit VLSI

6.2 Manufacturing

"Field" reliability

Charge/Lightening

EMI/EMC

Application to aerosevoelasticity, adaptive optics, controlled structures etc.

INTELLIGENT STRUCTURES CAN:

- Be deformed in an inertial reactionless process

  BEEF: 1500% plate thickness deformation

  BEEF: 70% area and 32 actuators achieved

- Incorporate "area averaging" tailored sensors

  BEEF: 120db/decade roll off with no phase

  BEEF: 1% error in quasistatic deformation with 4 strain sensors.

- Incorporate electronics

  BEEF: micro chips continue to work at the strain of structural failure.

- Achieve high gain robust control:

  BEEF: 35db reduction in broad band control

  BEEF: Control distributable to micro computers.

- Be Used for practical Aerospace applications

  BEEF: Aeroelastic Control

TECHNICAL PRESENTATION

"Panel Discussion on Smart Structures/Materials"

BY

Dr. Dan Inman

Department of Mechanical and Aerospace Engineering

University at Buffalo

State University of New York

PANEL DISCUSSION ON SMART STRUCTURES/MATERIALS

DAN INMAN

DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING
UNIVERSITY AT BUFFALO
STATE UNIVERSITY OF NEW YORK
BUFFALO, NY 14260

Wednesday 9 Oct. 91
AFOSR/NA Contractors Meeting

WITH THE HELP OF
Don Leo
Ralph Rietz
Jeff Dosch
Brett Pokines
Ephrahim Garcia

Mechanical Systems Laboratory

University at Buffalo

Issues

- is the complexity worth it?

  - performance comparisons, costs

    Yes, as experiments illustrate

    But not in all cases

- how "smart" can a structure be?

  - programmable structures

    - Remains to be developed
    - capable of simple computer logic

SMART/INTELLIGENT STRUCTURES

- adaptive structures: a structure with embedded sensors and actuators capable of changing its geometry as well as its physical properties.

- active structures: a controlled structure containing senors and actuators highly integrated into the structure.

- intelligent structure: an active structure also containing embedded sensors/actuators, incorporating control logic.

Current Experimental Activities in Vibration Suppression

- Slewing frame (AFOSR)

- Ribbed antenna (AFOSR)
  comparison of control schemes
  examples of need for smart structural control systems

- Nonlinear control using smart structures (slewing)

- Collocated self contained system Programmable Materials and
  Structures (ARO))

- New smart actuators (for truss control (NASA))

Thoughts for the FUTURE

- **Systematic Comparison of Control Theories for Use with Smart Structures**

- **Sort out when to use smart structures**
  - **versus passive control**
  - **versus conventional structural control systems**

- Optimal design issues (very successful for conventional systems)

- **Smart structures and full state feedback**

- **Smart structures and nonlinear control**

- **Experimental verification of models, algorithms and theories in complex configurations**

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ACTIVE DAMPING OF CANTILEVER BEAM
USING SELF-SENSING ACTUATOR

implementation .... *rate feedback*

$R = 20 \, k \, ohms$

$C = .061 \, \mu farad$

voltage follower -- 741 op-amp
amplifier -- Hewlett Packard 6824A
filter -- Ithaco 4302 24 dB/octave
analog computer -- Comdyn GP-6

single PZT
piezoelectric element
(sensor and actuator)

10 Hz corner

amplifier

filter

(gain = 27)

C

R

op-amp

−

Σ

10

R

op-amp

analog computer
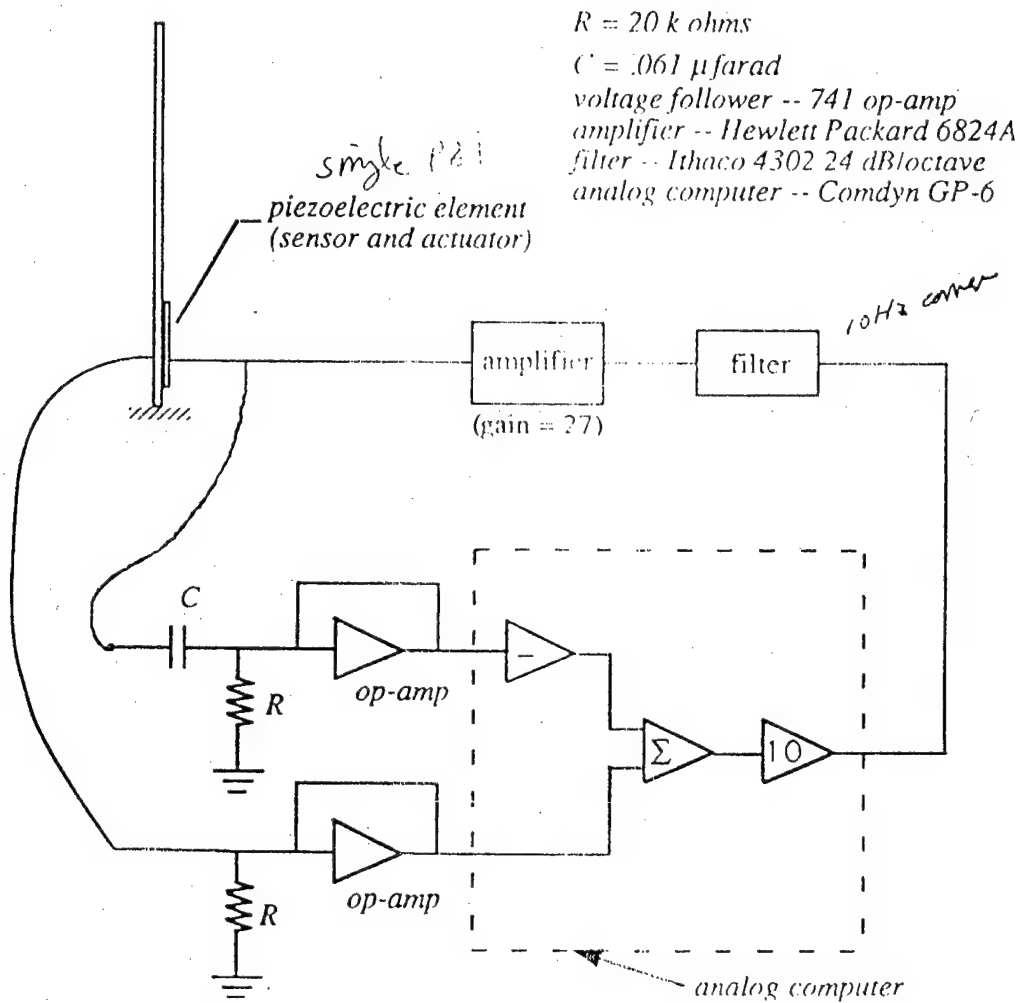
Cantilever Beam Experiment With Self-Sensing Actuator
(Rate Feedback)

· **provides completely collocated & therefore stable feedback**

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• Standard model of piezo Patch on Beam

• Effects of the piezo-actuators
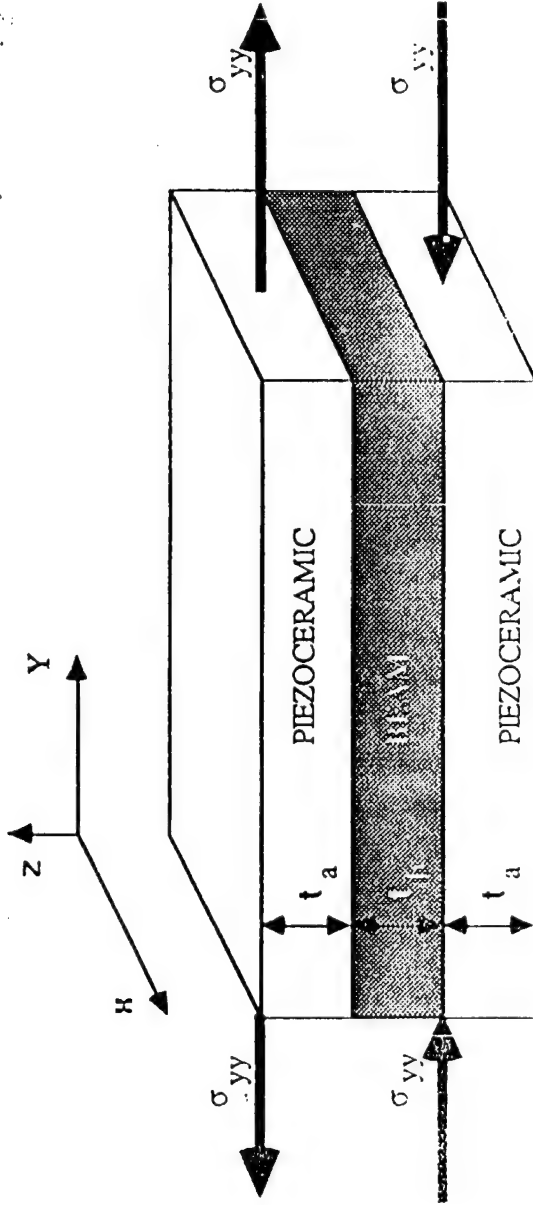
where: t_b - beam thickness

t_a - piezoceramic thickness

• distributed moment

$$\mathcal{M}(x,t) = b_a \int_0^L \sigma_{yy}\, z\, dz = b_a\, E_a d_{31}(t_a+t_b) V_p(t)$$

where: $V_p(t)$ - voltage applied across piezo actuator

$\mu = b_a\, E_a d_{31}(t_a+t_b)$

bending moment

How good is model
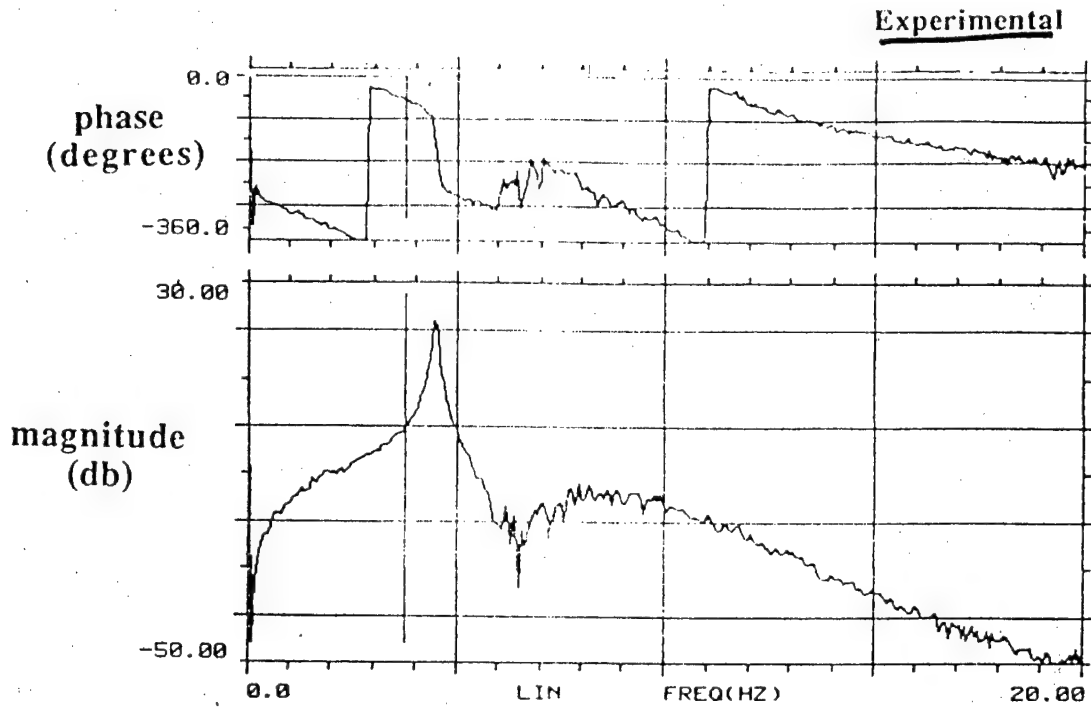
Match Mg. plot but note phase
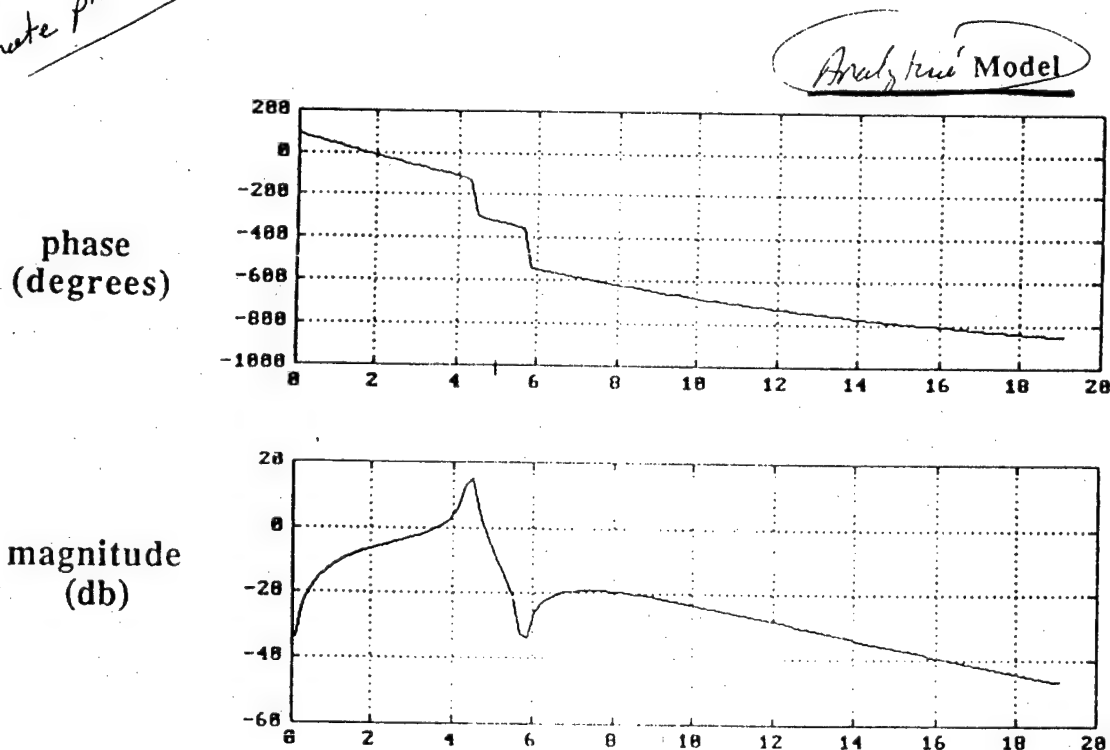
Analytic Model

· *Excellent comparison between analytical & EXP. MODEL*

FREQUENCY RESPONSE -- EXPERIMENTAL AND MODEL (self-sensing actuator)

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effect in time domain is more obvious

*ie
Simple velocity
feedback
works*

No Control

START

-0.5500   0.0   LIN   TIME(SEC)   16.00

Great improvement $t_s > 16 seconds$

$t_s \sim 5 seconds$ **With Rate Feedback**

START

PUT LIN

0.2000

-0.5000   0.0   LIN   TIME(SEC)   16.00
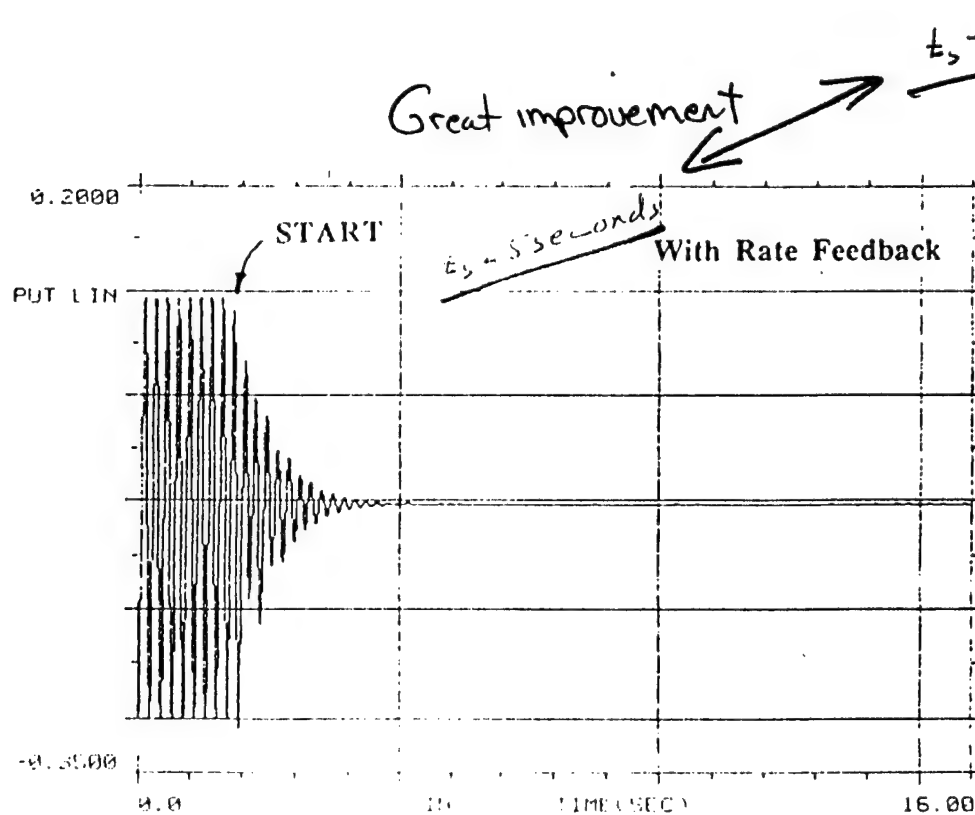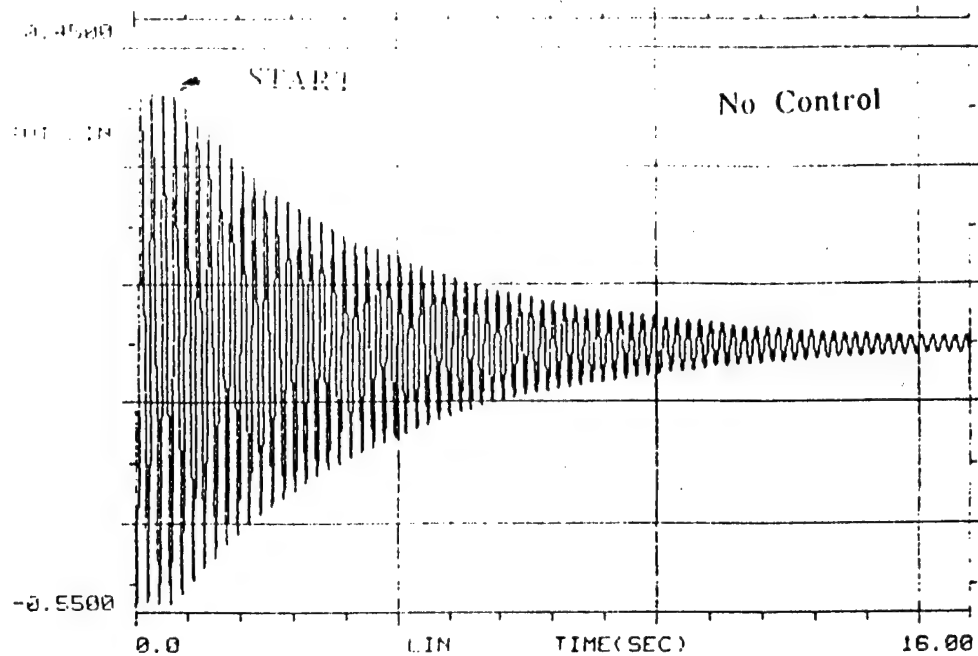
FREE RESPONSE OF CANTILEVER
BEAM   (self-sensing actuator)

possible to greatly improve
performance (Z_3)

· result obvious from matrix elements

USE OF SMART STRUCTURE IMPROVES PERFORMANCE
IN SLEWING MANEUVER

by 50%

STRAIN RATE

RT INPUT LIN
CH 1
:X

8.000

-8.000

0.0   LIN   TIME(SEC)   8.000

SAME MANEUVER WITH SMART MATERIAL
(PIEZOELECTRIC CERAMIC)

STRAIN RATE

0.0   LIN   TIME(SEC)   8.000

POSITION DERIVATIVE CONTROL OF 10° SLEWING MANEUVER

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Slewing Frame Experiment

Frame Structure

DC Motor + Tachometer

Active Strut

Active Strut

Position Sensor

1 foot

Mechanical Systems Laboratory

University at Buffalo

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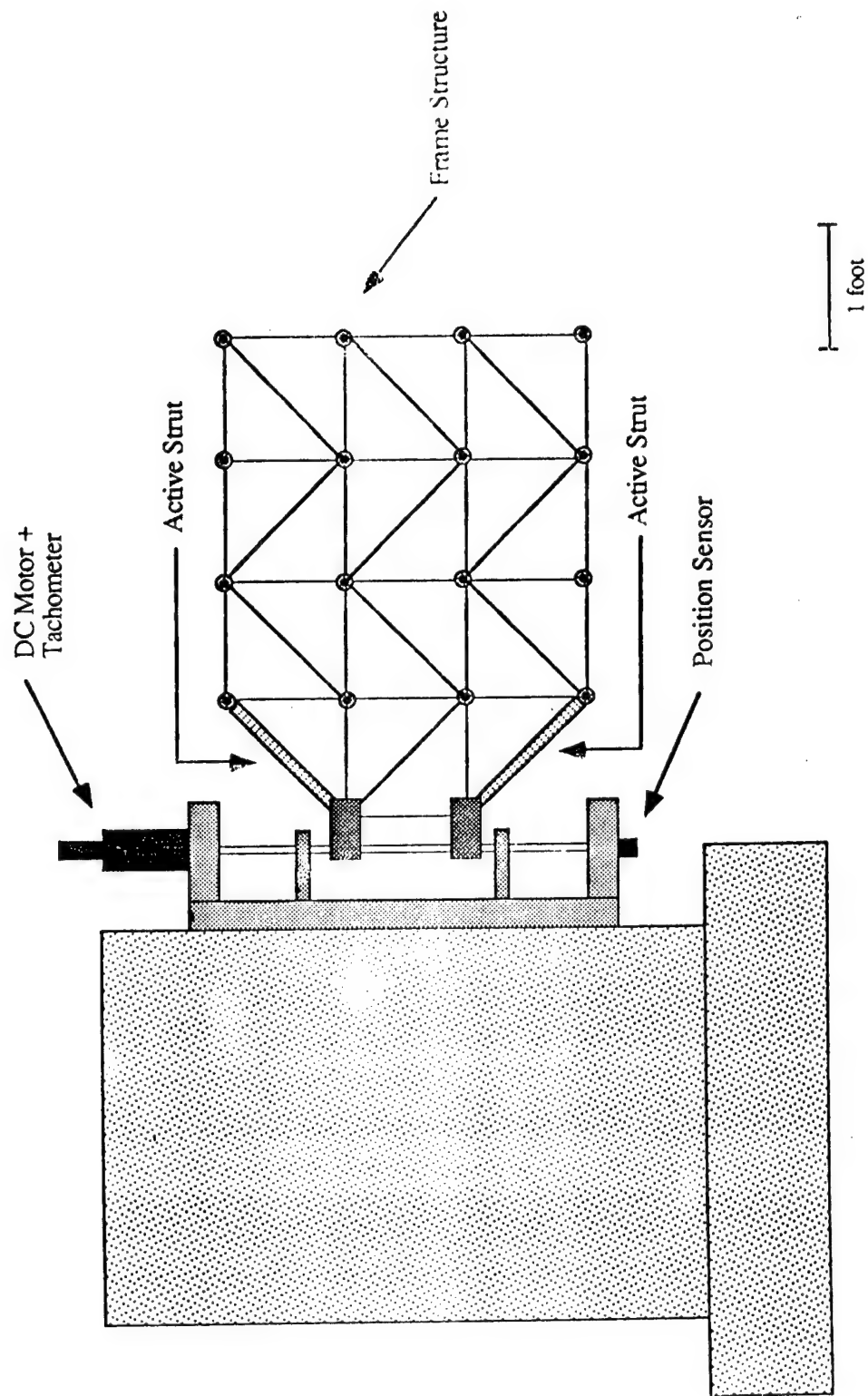
Schematic of Slewing Frame Control

Structural Feedback
from piezoceramics
using Self-Sensing
Actuators

Negative Strain Rate Feedback
Positive Position Feedback
Modal Electronic Dampers
H_∞

Active Strut

Frame

DC Motor

+ +

Slewing Command

Step Input
Torque Shaping

Angular Rate and Position Feedback
LQR
H_∞
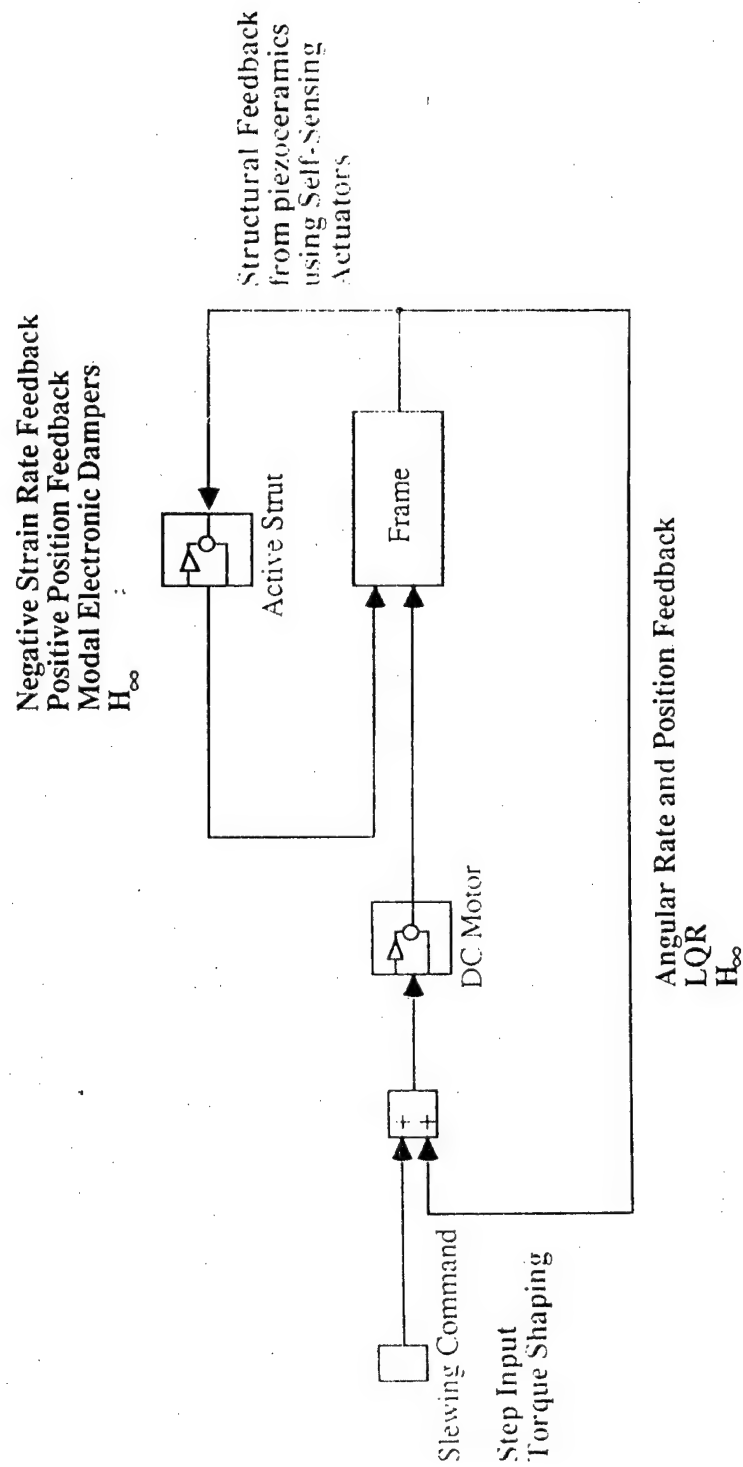
Simulated Responses during a 30° slewing maneuver
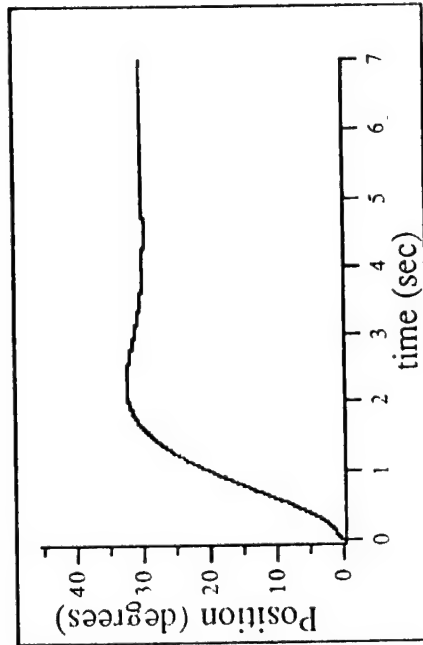
Angular Position of the Frame
with PD Control on the Motor

Structural Response
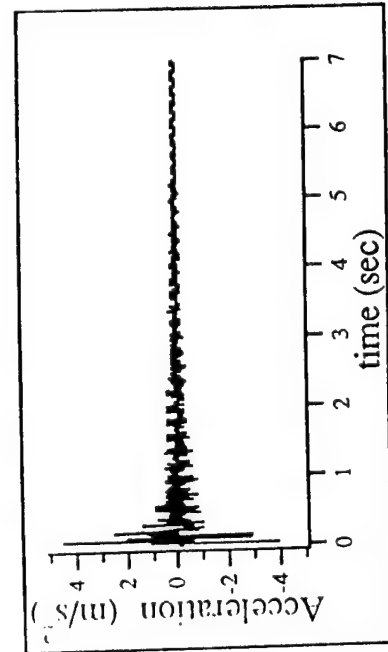
Active Strut off
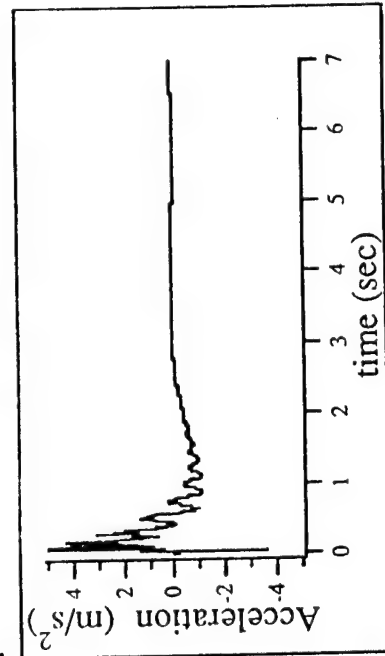
Active Strut on with PPF Control.

So where's the Beef?

- SEE Mr. Ed ; Mr. Brains, Dave

- IN providing an ability to place sensors and actuators anywhere (full state feedback)

- in changing the way one thinks about structural control problems (increased performance expectations)

- providing solutions to a structural control problem that didn't have a practical solution before

- IN providing the potential for substantially improving nonlinear control of structural systems

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Summary

- some examples illustrating the use of "smart" structures have been presented

- active structures provide increased performance over passive structures

- full state feedback can be approached by using active structures

- complicated structures with high modal density can be controlled using active structures

TECHNICAL PRESENTATION

"Characterization and Modeling of PZT"

BY

Dr. Craig Rogers
Center for Intelligent Material Systems and Structures
Virginia Polytechnic Institute and State University

Outline

- Physics of Piezoelectricity

- Current Modeling Approaches

- Macroscopic Phenomenological Modeling of Hysteresis of PZT

- Investigation of the Long-time Performance of PZT

Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

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Definition

Piezoelectricity is the property of a crystal to exhibit electric polarity when subjected to stress. The converse piezoelectric effect is referred to as the generation of mechanical deformation as a result of applied electric field.
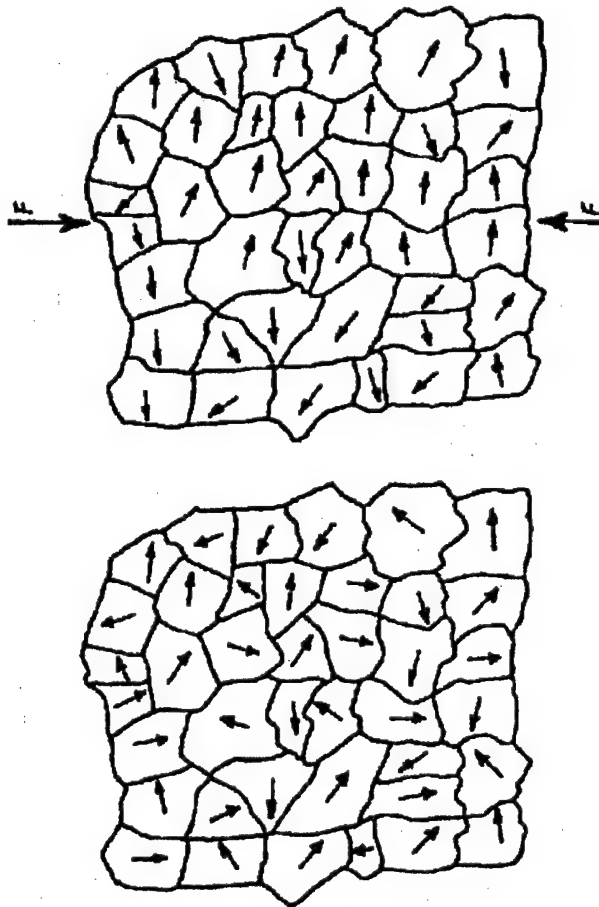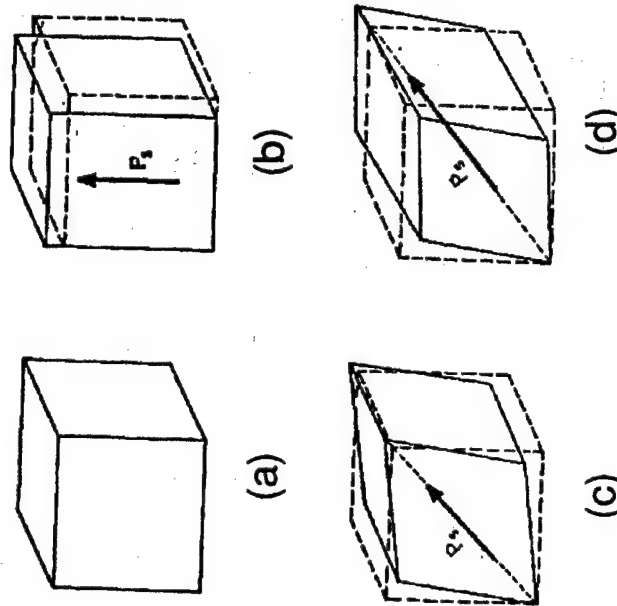
Converse Piezoelectric Effect

(a) Cubic phase, stable above the Curie temperature, no piezoelectricity; (b) Tetragonal phase; (c) Orthorhombic phase; and (d) Rhombohedral phase. Dotted lines represents the original crystal. Solid line indicates the dimensional change upon polarization, P_s.

Piezoelectric Effect

Electro-Mechanical Behavior of PZT

Hysteretic Behavior (DC)

Piezoelectric Effect
(Sensor Application)
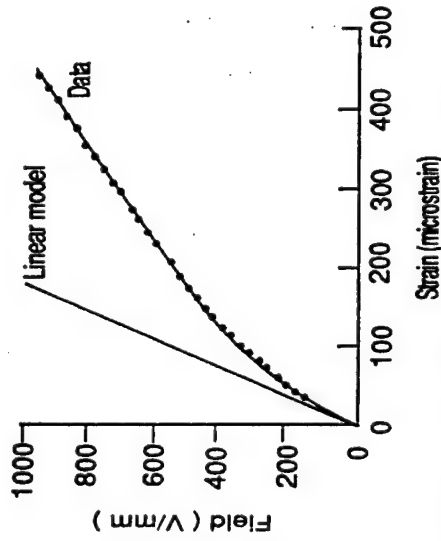
Induced Strain vs. Electric Field
Nonlinearity at Higher Field (After Crawley)
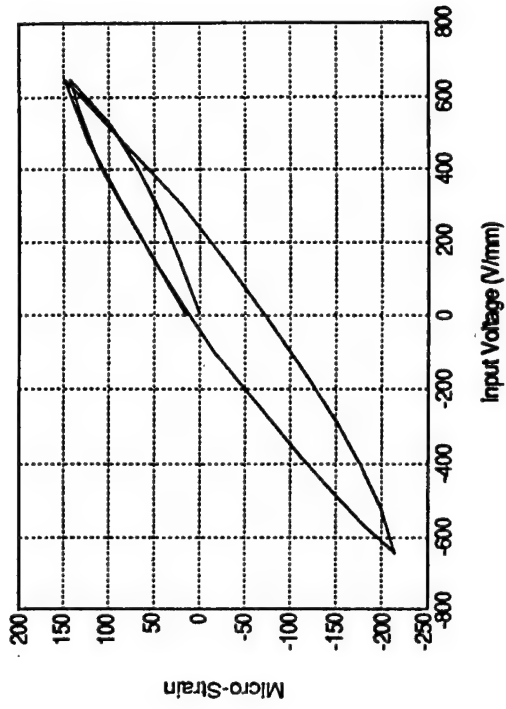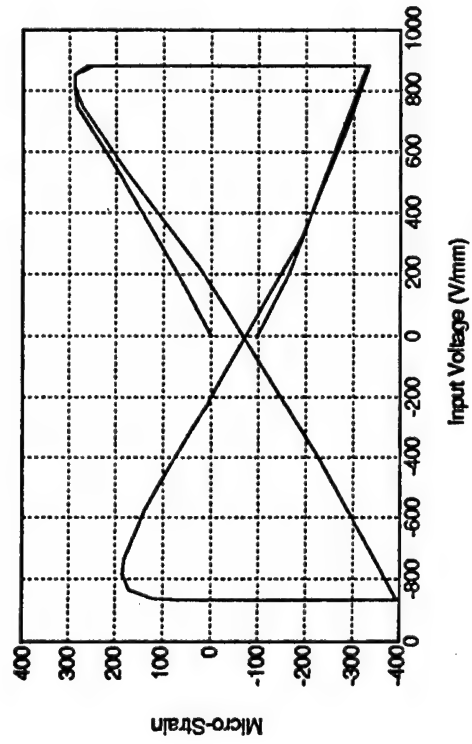
Coercive Voltage and Polarization

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Essence of Piezoelectricity

- The piezoelectric effect can be described as re-orientation of electric dipole moment when subjected to an electric field or external stress.

- Each crystal may consist of several "domains" which have the same dipole direction.

- The piezoelectric effect and its converse effect are governed basically by the nucleation and wall motion of these domains.

- The nucleation and wall motion of domains are a dynamic process. A time constant is associated with this process. The nonlinearity and Hysteresis of PZT is a result of delayed nucleation and domain-wall motion.

Polished and Etched Surface of Unpoled PZT

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Discussion of Domain Movement

Domain Vectors

180° Domain   90° Domain

Domain Vectors

90° Domain reversal

Dimension change is a result of 90° domain switching (or reversal).
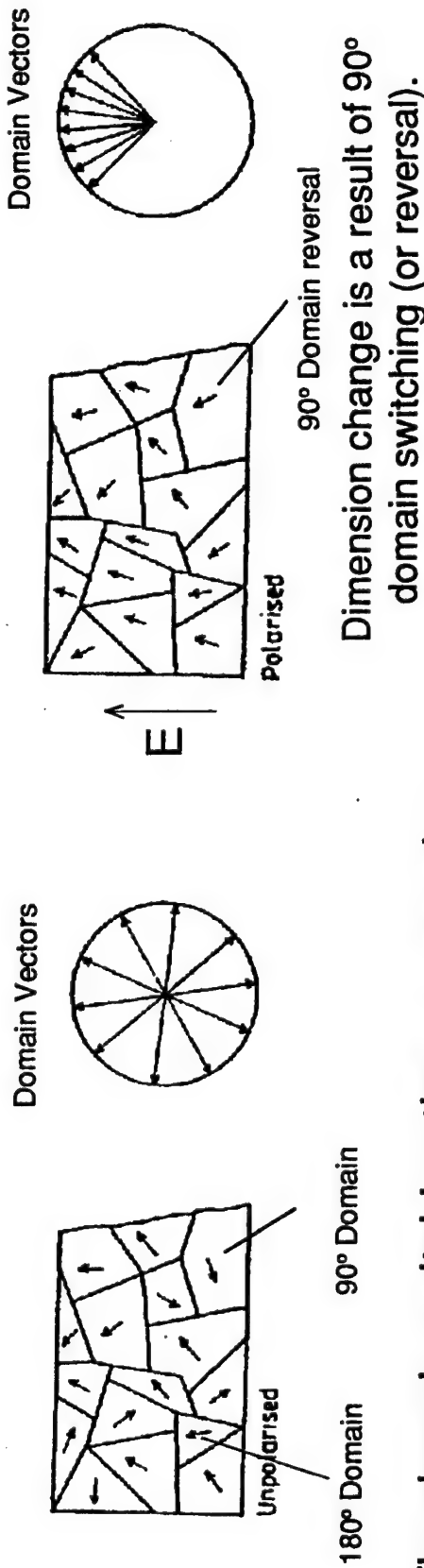
The domain switching time, t_s, consist of domain nucleation time, t_n, and domain-wall motion time, t_d. These time constants are function of field and temperature.

$$t_n = t_\infty \exp(\alpha/E)$$

$$t_d = C/E$$

$\alpha = \alpha(T); \ C = C(T)$ (mobility of domain motion)

Region I: Domain nucleation
Region III: Domain-wall motion
Region II: Mixed motion and nucleation
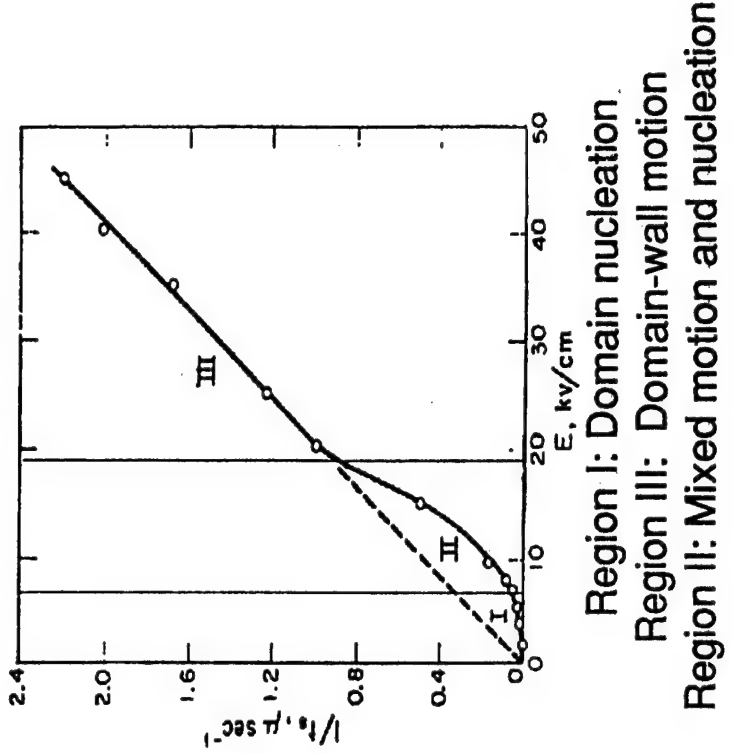
Thermodynamics of PZT
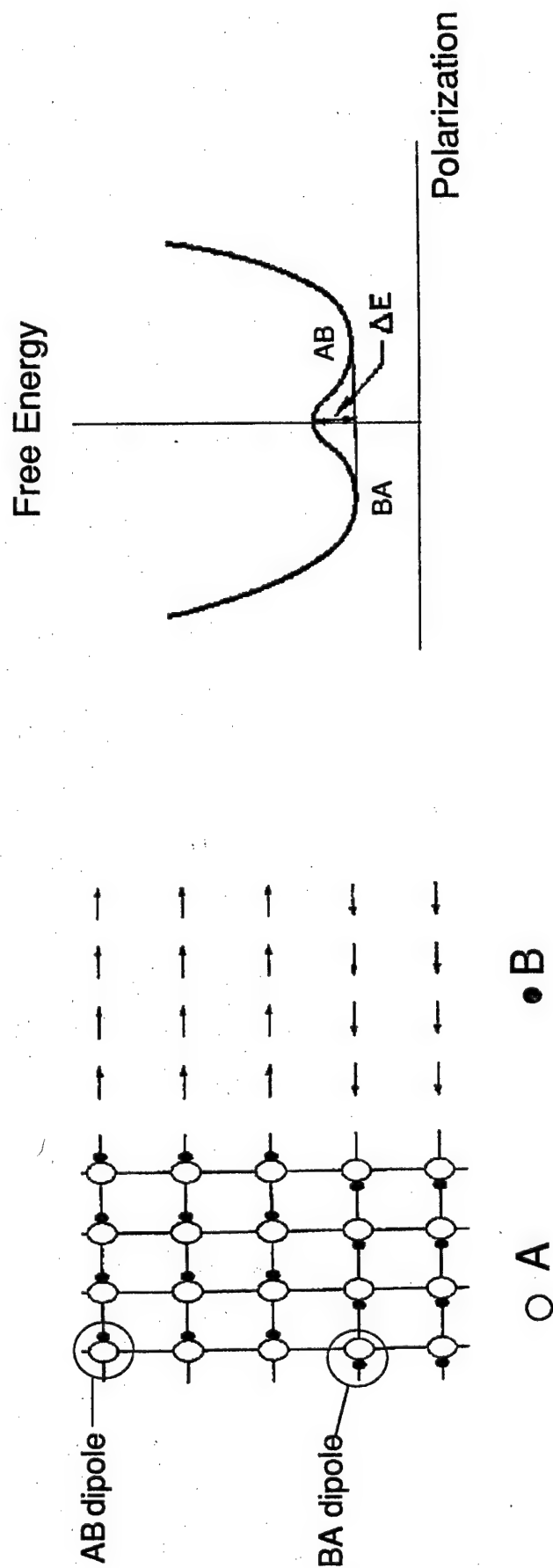
A ion carries negative charge and B ion carries positive charge. AB dipoles and BA dipoles are stable and correspond to the two minimums on the free energy vs. polarizatoion curves. Under an external electric field in AB direction BA dipole will be reversed. The energy required to reverse this dipole will be ΔE (the barrier energy in the energy vs. polarization curve).

Thermodynamic One-Dimensional Modeling of Piezoelectricity

- Thermodynamic variables: stress (T), strain (X), electric field (E), polarization (p) or electric displacement (D)

- Free energy (in terms of stress and field):

  $G(T,E) = s^E T^2/2 + \varepsilon^T E^2/2 + dTE$ + higher order terms of T and E

  s^E: compliance matrix at E=0,
  ε^T: permitivity at T=0, and
  d: piezoelectric constant

- Constitutive equations:

  $X = \partial G/\partial T; \quad D = \partial G/\partial E$

- Linear constitutive equation (neglecting the higher order effect of T and E)

  $X = s^E T + d E$
  $D = d T + \varepsilon^T E$

Modeling of Hysteresis and Nonlinearity with Thermodynamics

Assuming the following free energy in terms of stress and polarization:

$$G(T,p) = s^p\, T^2/2 + \underline{\chi^T p^2/2 + bpT} + \xi^T p^4/4 + \zeta^T p^6/6$$

Corresponding to linear piezoeletricity

χ^T: reciprocal dielectric susceptibility, b=d/ε^T

Stress free: $\quad G(T,p) = \chi^T p^2/2 + \xi^T p^4/4 + \zeta^T p^6/6$

$$E = \partial G/\partial p = \chi^T p + \xi^T p^3 + \zeta^T p^5$$

Unstable Region

(S=bP)

G

Unstable Region

p
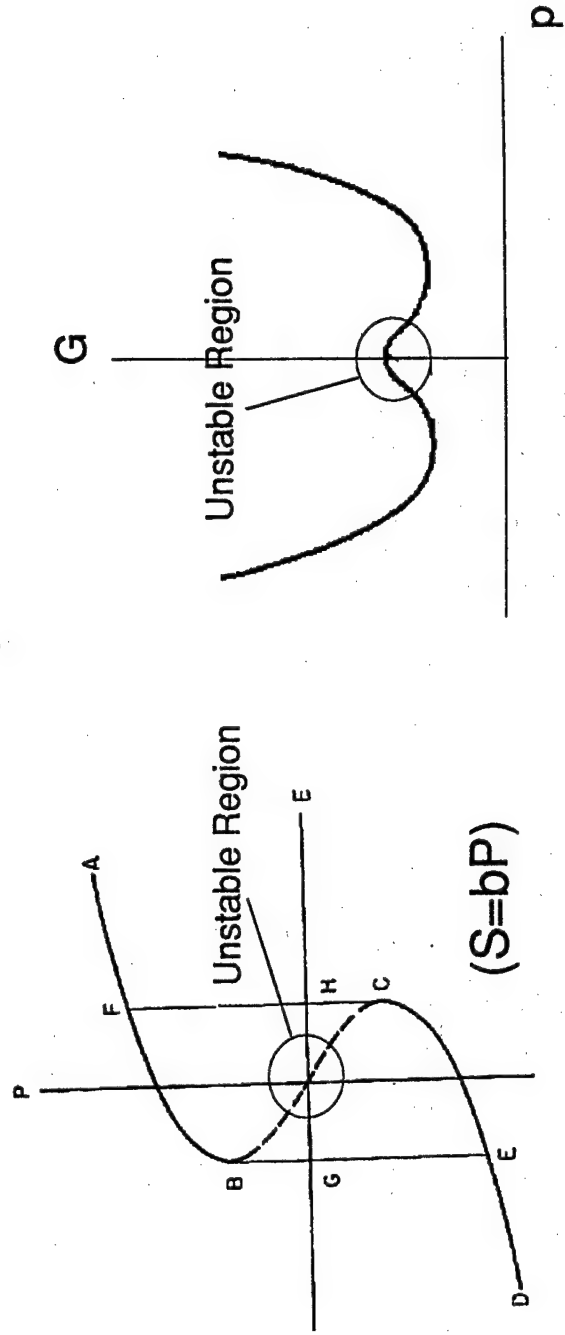
Macroscopic Modeling of Piezoelectricity

- The cause of the hysteresis in PZT is the delayed re-orientation of dipole moments, or the dynamics process of domain nucleation and domain-wall motion.

- This modeling approach is based on both macromechanics and micromechanics. The investigation of domain switch, the microscopic aspect of PZT, provides the foundation for the mechanical constitutive relations for PZT.

$$T=T(S,\theta,E,N)$$

$$D=D(S,\theta,E,N)$$

$$\dot{N}=f(S,\theta,E,N)$$

S: strain; T: stress;

θ: temperature; N: effective dipole number

(After Chen and Montgomery,1980)

Constitutive Modeling of Shape Memory Alloys

The basic goal of our constitutive modeling effort is to predict and describe how the microstructure affects the macromechanical behavior of the material and create models that are dependable for actuator and sensor design and can be incorporated into macromechanical models.

Example: Constitutive modeling of shape memory alloys (Muller's vs. Va. Tech)

Helmholtz Free Energy

$$\Phi = E - TS$$

Transformation Kinetics
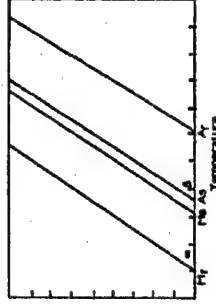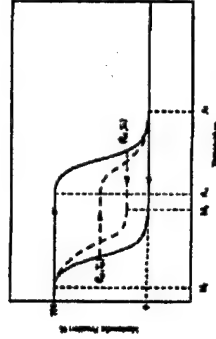
$$\begin{cases} \xi = 1 - \frac{1-\xi_A}{2}\exp[a_M(M_0 + \frac{\sigma}{C_M} - T)^n] & M_\sigma^g \geq T \geq M_f^g \\ \xi = \frac{1-\xi_A}{2}\exp[a_M(T - \frac{\sigma}{C_M} - M_0)^n] & M_\sigma^s \geq T \geq M_\sigma^g \end{cases}$$

Thermodynamics

$$(\frac{\bar{\sigma}}{\rho_0} - \frac{\partial\Phi}{\partial\epsilon})\dot{\epsilon} - (S + \frac{\partial\Phi}{\partial T})\dot{T} - \frac{\partial\Phi}{\partial\xi}\dot{\xi} - \frac{1}{\rho_0 T}f^{-1}q_{sur}\frac{\rho_0}{\rho}\frac{\partial T}{\partial X} \geq 0$$

Constitutive Equations

$$\dot{\bar{\sigma}} = \frac{\partial\sigma}{\partial\epsilon}\dot{\epsilon} + \frac{\partial\sigma}{\partial T}\dot{T} + \frac{\partial\sigma}{\partial\xi}\dot{\xi} = D\dot{\epsilon} + \Theta\dot{T} + \Omega\dot{\xi}$$

Potential Well and Minimization of Free Energy

Statistical Physics

$$\Delta = \frac{1}{\sqrt{2}}(N_{M-}\Delta_{M-} + N_{M+}\Delta_{M+} + N_A\Delta_A)$$

Constitutive Equation:

$$\Delta = \frac{N}{\sqrt{2}}\frac{e^{(\frac{P\Delta+A}{kT})}\sum[\Delta e^{(\frac{P\Delta-\phi(\Delta)}{kT})}] + e^{(-\frac{P\Delta+A}{kT})}\sum[\Delta e^{(\frac{P\Delta-\phi(\Delta)}{kT})}]}{e^{(\frac{P\Delta+A}{kT})}\sum e^{(\frac{P\Delta-\phi(\Delta)}{kT})} + e^{(-\frac{P\Delta+A}{kT})}\sum e^{(\frac{P\Delta-\phi(\Delta)}{kT})}}$$

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Experiment Setup for Investigation of PZT

- Investigation of the dynamic behavior of PZT (frequency: 20 to 500Hz)

- Temperature influence (<400°C)

- Maximum voltage output 250 volts

- Computer data acquisition includes voltage, temperature, and strain.

- Fatigue test (free-free PZT and constrained PZT)

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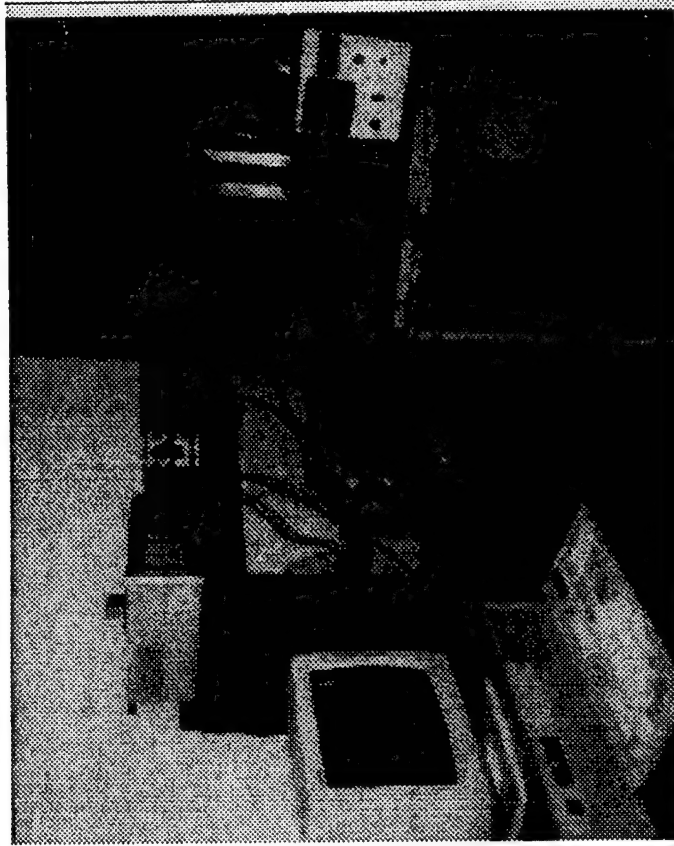
Hysteresis of PZT at Various Frequencies

Hysteretic Behavior (DC)
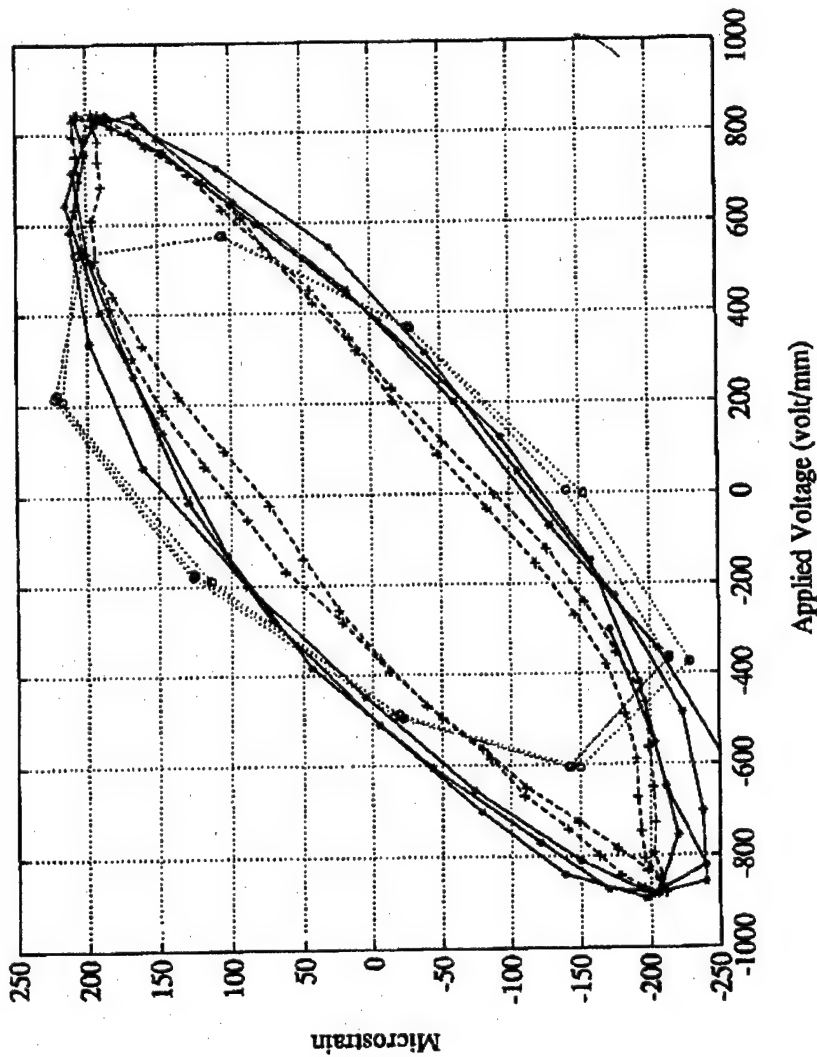
o 500 Hz; * 100 Hz; + 20 Hz
Temperature: 22°C

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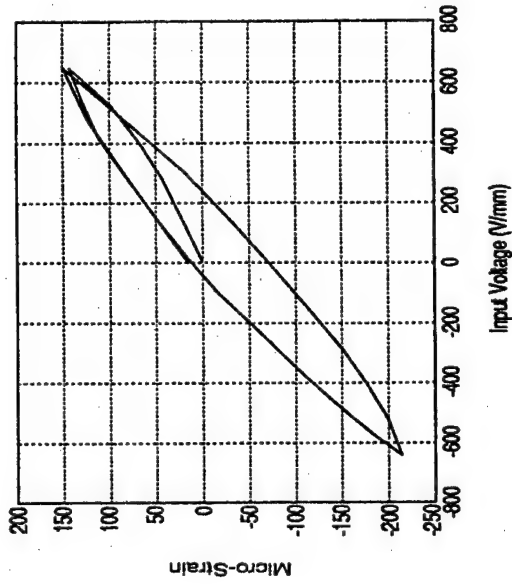
Hysteresis of PZT at 50°C and 100 Hz

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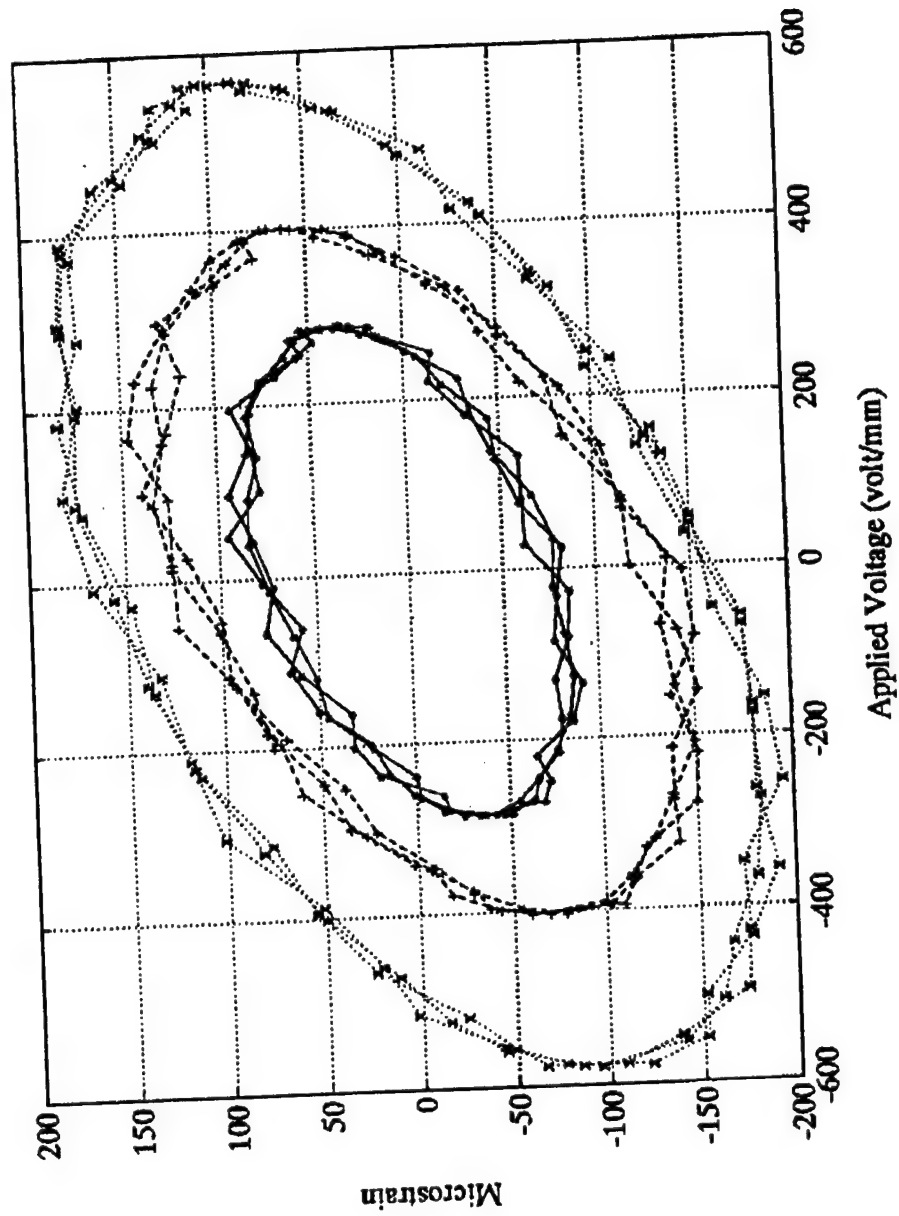
Coupled Electro-Mechanical Modeling of Hysteresis

The hysteresis of PZT under a sinuoidal AC voltage is a ellipse. The profie of the ellipse may be described by

$$A V^2 + BX^2 + CVX = 1$$

$A=1/V_c^2; \quad B=1/X_r^2;$
$C=(1/V_c^2-1/X_r^2) \, 2 \, d^*/(1-d^{*2})$

X_r: remanent strain
V_c: coercive voltage
d^*: hysteretic piezoelectric constant

The remanent strain, coercive voltage, and hysteretic piezoelectric constant are functions of temperature, voltage frequency, the amplitude of voltage, and properties of the electric circuit, namely the impedance of circuit.

Investigation of the Fatigue of PZT
Electrical Breakdown

Under AC field, the number of trapped defects at test cycle n:

$$\frac{dN}{dn} = \lambda \Delta t \; ae^{-Q/kT} \; e^{aE_\lambda} \; \Delta E_i$$

Internal field difference is reduced by
1) Defect accumulation
2) Dielectric viscosity (β)

$$\frac{d\,\Delta E_i}{dN} = -\gamma\beta\lambda ae^{-Q/kT} e^{aE_\lambda} \; \Delta E_i = -\xi \; \Delta E_i$$

At interface, polarization is reduced by defect accumulation:

$$P = P_o \left[\frac{\xi^2 \Delta t}{\gamma \beta} \Delta E_{io} \, n + 1 \right]^{-\nu/\xi} = P_o (An + 1)^{-m}$$

where
P_o : initial polarization
ΔE_{io} : initial internal field difference
A : piling constant
m : decay constant

PZT films

Thickness of the film: 0.3 μ

Investigation of the Fatigue of PZT
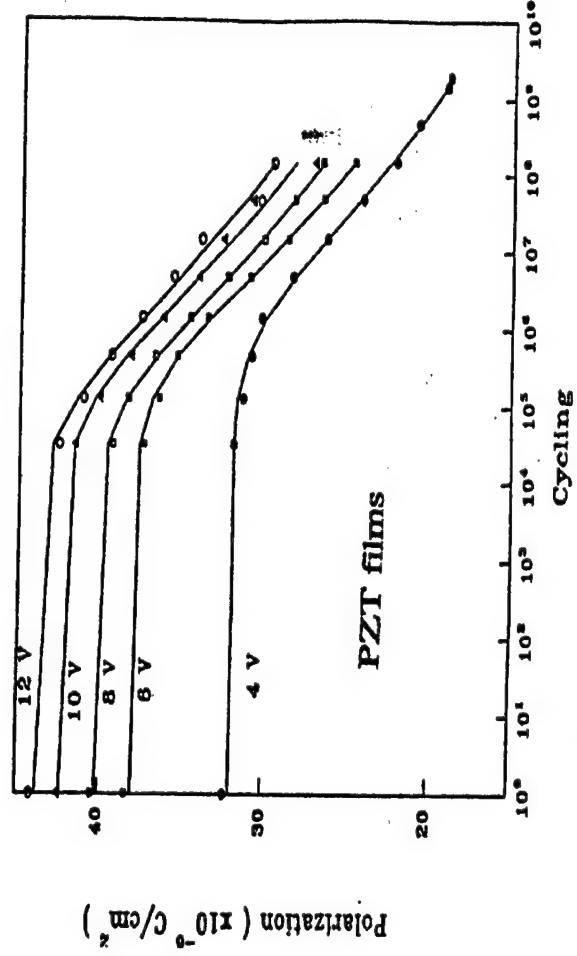
Free-Free PZT
Field=800 volt/mm
Frequency=100 Hz
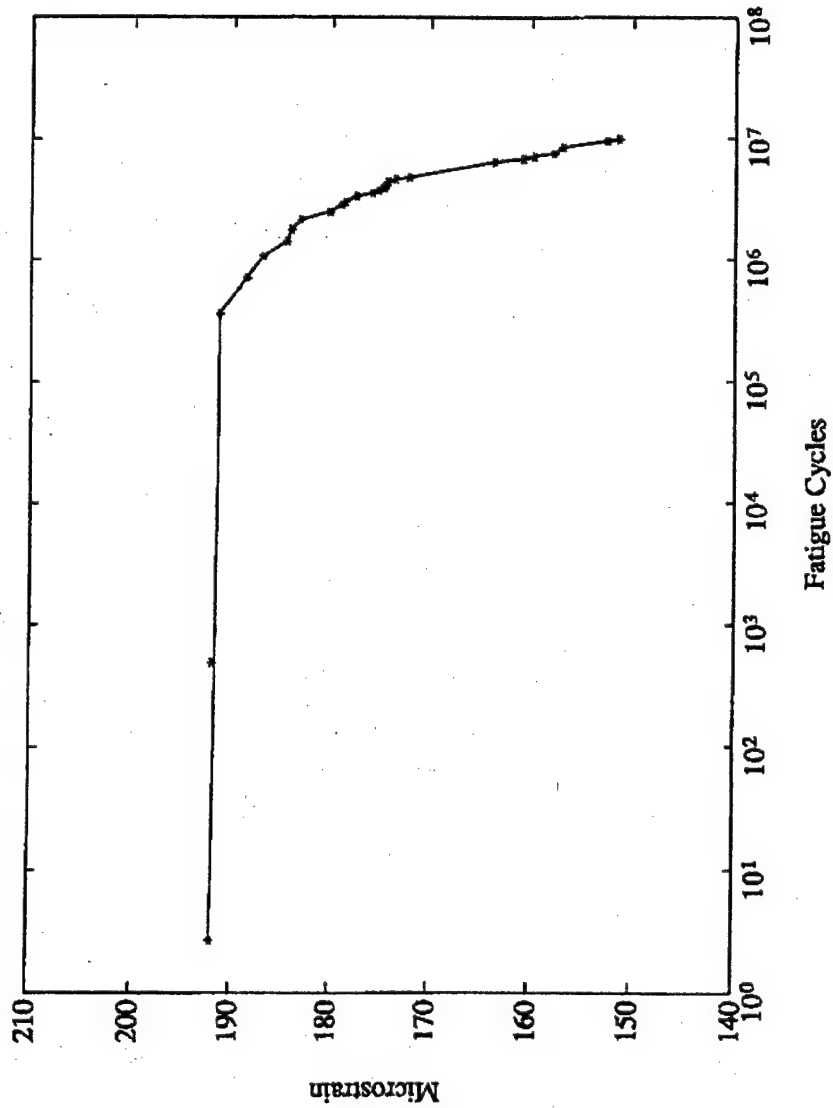
T=70°C
20% Reduction of Induced
Strain at 10^7 Cycles

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What happens if voltage is too high?
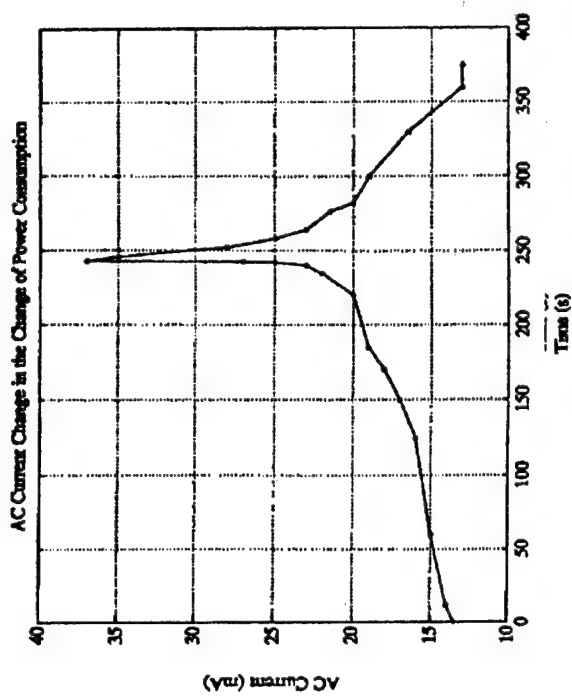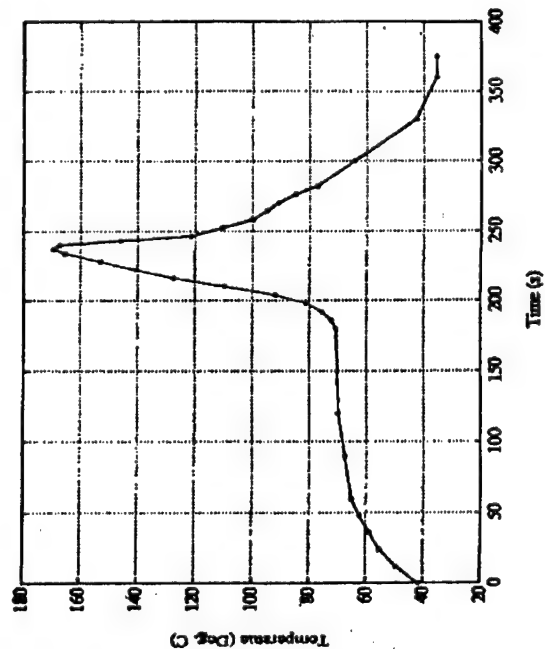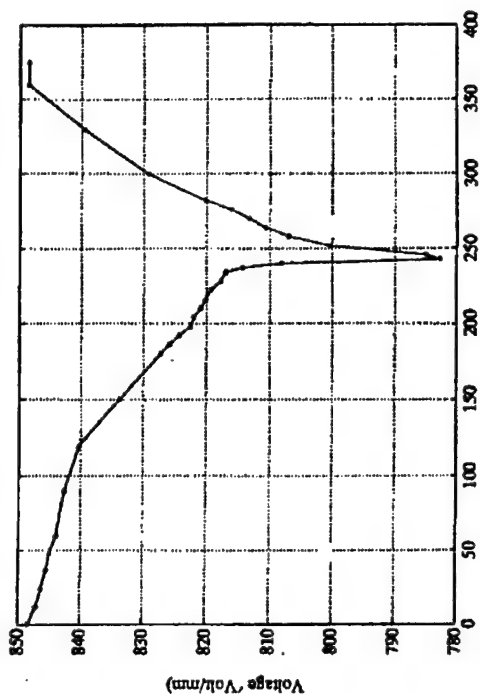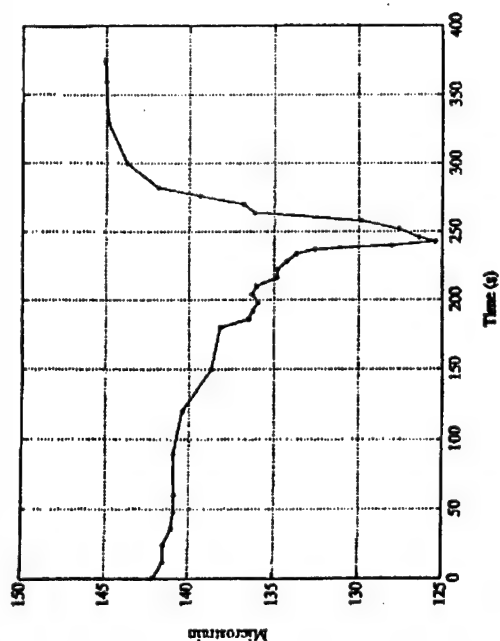
Fan cooling starts at 240 second.

Preliminary Experimental Apparatus for Fatigue Control Demonstration.
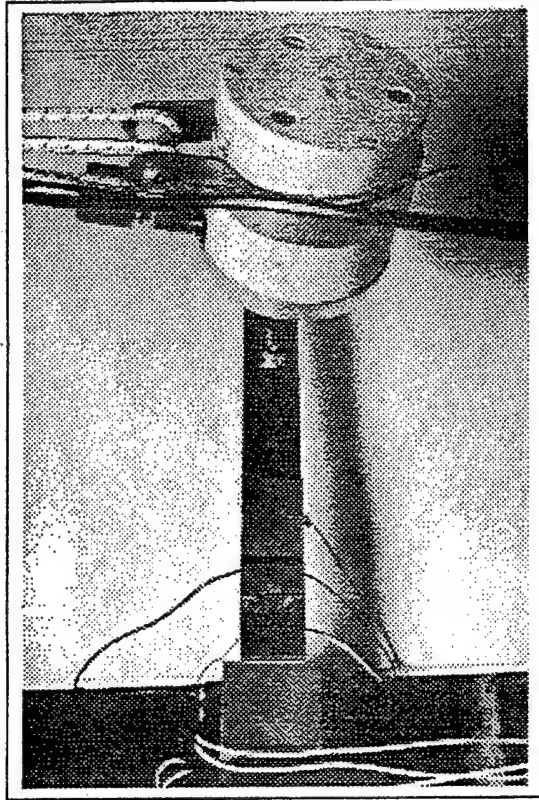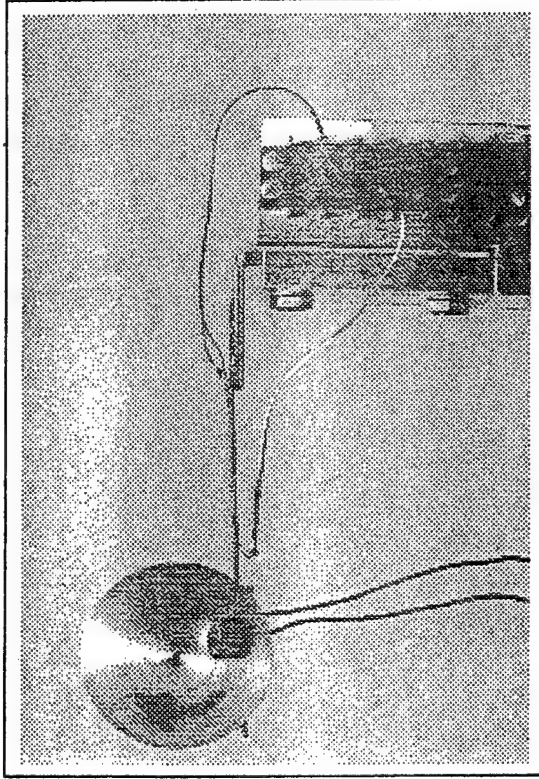
In order to prove an initial concept that we developed, namely that vibration control at mechanically fastened and bonded joints would significantly increase fatigue life, we built two demonstration units. One used a rotating unbalance to produce the alternating stress and the other a force shaker. The results of the *initial experiment showed a fatigue life increase of over one order of magnitude.* Both were useful in identifying experimental issues and problems that will need to be addressed when further research commences. The initial experimental demonstration is the first known active fatigue control experiment.

Application Issues Associated with PZT

- Fatigue
  Electrical Breakdown
  Electrode Breakdown
  Mechanical Breakdown
  Design of Multi-layered Actuator

- Hysteresis and Nonlinearity

- Energy Dissipation
  Temperature Effects
  Changes of Impedance

- Authority

- Power Supply and Control Circuit
  Multi-channel Control
  Coupled Mechanical and Electric Circuit Design

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Summary

- Revelation of the essence of piezoelectricity

- Review of the constitutive modeling of PZT

- Investigation of the hysteresis behavior of PZT considering the properties of electric control circuit

- Preliminary investigation of the fatigue properties of PZT

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Future Work

- Further experimental and theoretical investigation of the influence of temperature, frequency, and electric circuit properties on the hysteretic behavior of PZT

- Further development and experimental verification of the elliptic model

- Further investigation of the constitutive relation of PZT based on domain switching theory

- Establishing the correlation between the nonlinear and hysteretic behavior and domain switching process

- Investigation of the long time performance of PZT (mechanical breakdown and electrical breakdown)

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TECHNICAL PRESENTATION

"Active Composite Structures"

BY

Dr. Terrance Weisshaar

School of Aeronautics and Astronautics

Purdue University

Active composite structures -

Aeroservo/control/structure tailoring issues

Terrence A. Weisshaar

Steven M. Ehlers

School of Aeronautics and Astronautics

Purdue University

West Lafayette, Indiana

Active aeroelasticity

Evolution of Aeroservoelastic Design:

Conventional Isotropic Materials

Inexpensive

Advanced Composites

Weight savings
Tailoring

Adaptive Structures

Self actuating structure
(Wing warping)

Mechanical Actuators

"Smart" Wing Skins or Panels:

Augment control surfaces (trim)
Divergence avoidance
Flutter suppression
Panel flutter alleviation
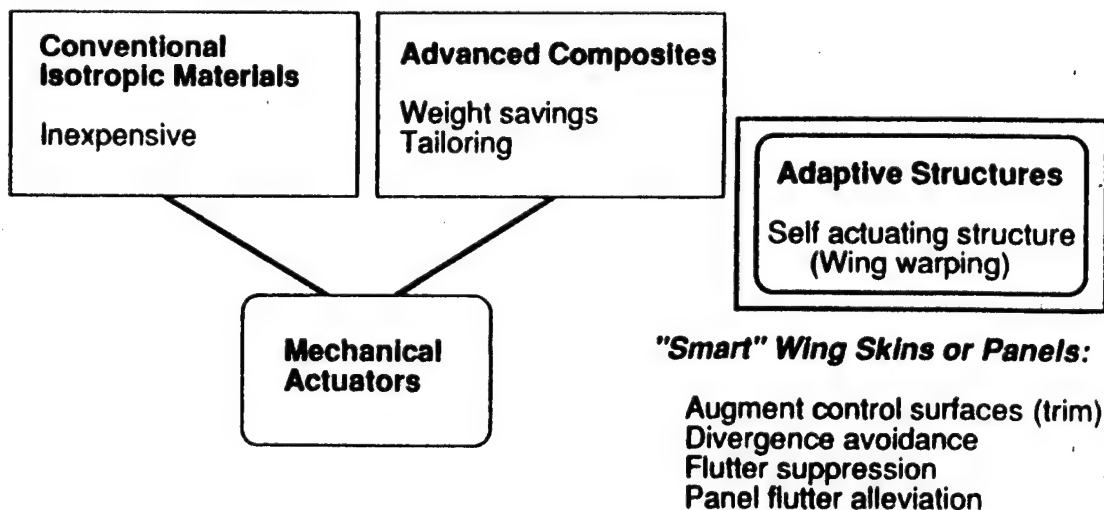
Active aeroelasticity

Thesis

Active materials can be integrated into lifting surfaces to improve design performance.

***Result* - Establish a role for active materials in flight vehicle stuctures. Identify scientific issues.**

Integration issues - "abilities"

❑ **material suitability**

❑ **availability**

❑ **reliability**

❑ **manufacturability**

❑ **feasibility**

Integration issues - structures

stiffness orientation exploitation

actuator location

size

strength

Integration issues - controls

❏ **formulation - classical - modern**

❏ **sensor/control location**

❏ **size**

❏ **optimization**

Actuation / performance issues

Macroactuation - deforming a large surface to change lift. How large? How much?

Microactuation - deforming a small, localized area to produce local flow changes. Where? Why?

Active aeroelasticity

Measures of performance

Lift

Drag

Stability -

local - global - static - dynamic

Active aeroelasticity

Actuation / performance issues

Macroactuation - deforming a large surface to change lift. How large? How much?

Microactuation - deforming a small, localized area to produce local flow changes. Where? Why?

Examples

Static wing lift effectiveness

Panel flutter suppression

Transonic drag reduction

Shock oscillation control

Static Aeroelasticity
Divergence Suppression
Lift Effectiveness Control
Control Effectiveness

Dynamic Aeroelasticity
Flutter Suppression
Gust Load Alleviation
Transient Behavior

Aerodynamic Shape Control
Laminar Flow Control
Shock Wave Positioning

Stability and Control
Control Surface Augmentation
Flexible Vehicle Stability
Microtrim

Controlled aircraft wing

Voltage Gain

Kp

Sensor

Active Material
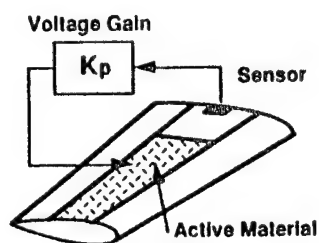
- Piezoelectric materials generate strains under applied electric fields.

- Feedback system senses wing root loads and applies a constant electric field to the piezoceramic material actuator.

- Actuation causes change in wing stiffness and static aeroelastic characteristics.

DIVERGENCE

Dynamic Pressure $\frac{q}{q_d}$ 1.0

Stable region

Unstable region

Divergence of a Non-Adaptive Wing

0

Voltage Gain, Kp

⊔⊔⊔⊔ Divergence Boundary   ▲▲▲ Actuator Saturation Limit

LIFT EFFECTIVENESS

decreasing lift effectiveness

Unstable region

Dynamic Pressure $\frac{q}{q_d}$ 1.0

1.0

Increasing lift effectiveness

0

Voltage Gain, Kp
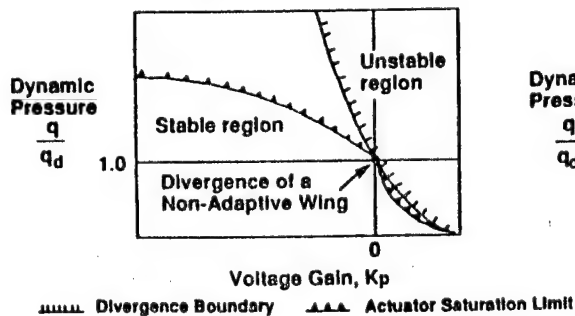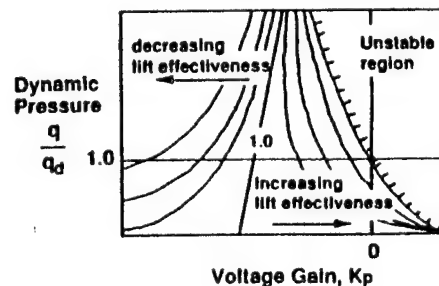
Active aeroelasticity

ADAPTIVE WING STATIC AEROELASTICITY
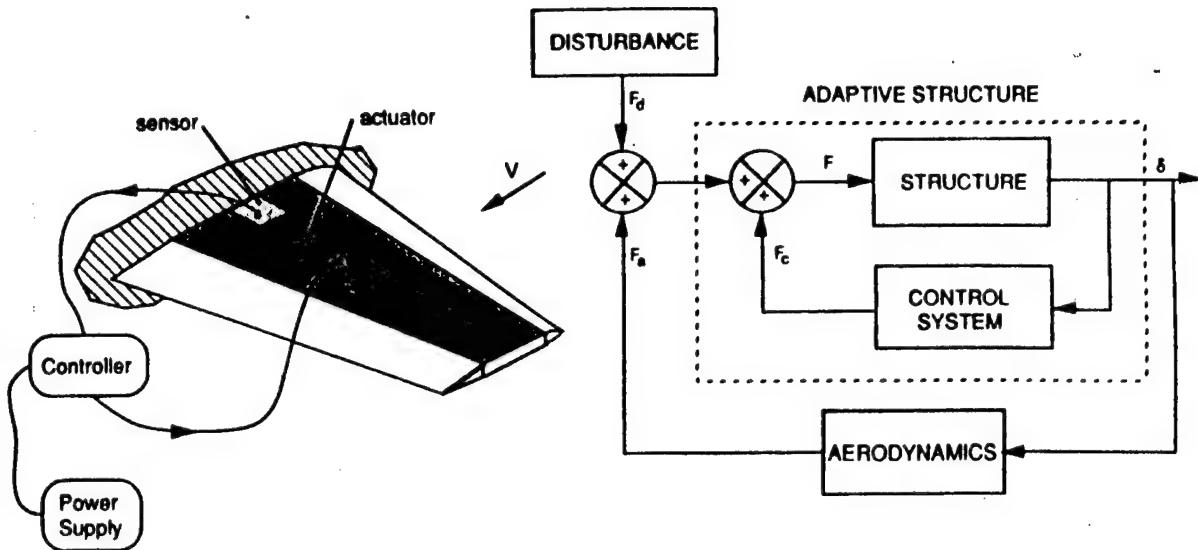
$$S(v) - C(v) - A(q,v) = Q_d$$

Objectives

Determine nondimensional parameters that influence aeroelastic performance

Assess available active material capabilities to change aeroelastic performance

Suggest goals for new active materials

Active aeroelasticity
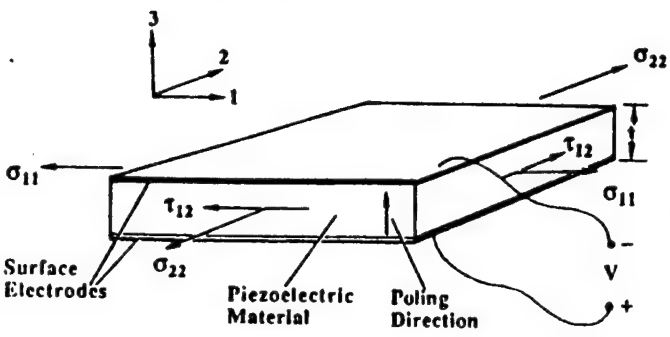
Material	Stimulus
Piezoelectric	**Electric Field**
Electrostrictor	Electric Field
Magnetostrictor	Magnetic Field
Shape Memory Effect	Temperature
Electrorheological Fluids	Electric Field
Thermoelastic Materials	Temperature
Optical Fibers	----------

Voltage induced strain

Active aeroelasticity

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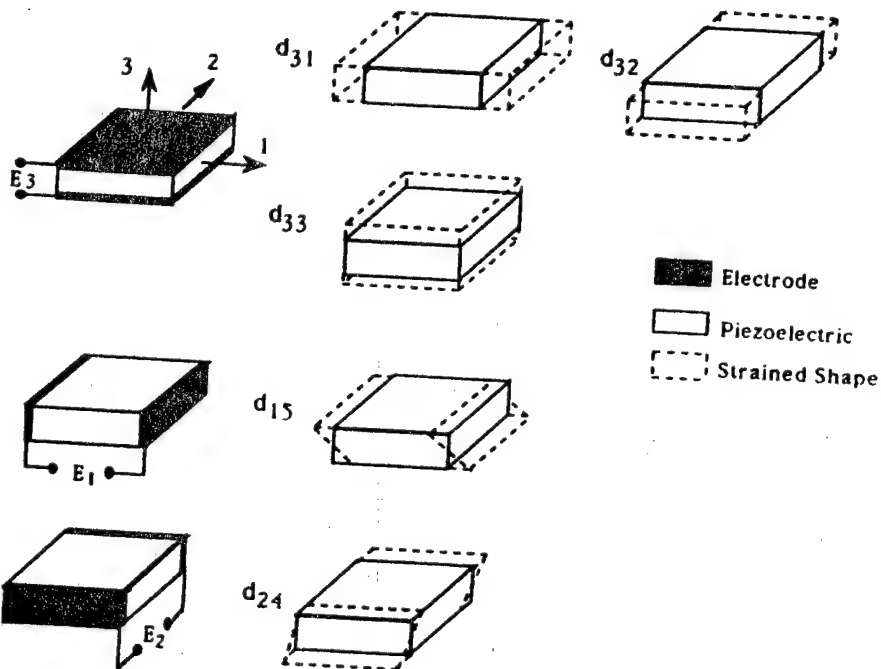
THIN LAYER PIEZOELECTRIC

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11}^E & S_{12}^E & 0 \\ S_{12}^E & S_{22}^E & 0 \\ 0 & 0 & S_{66}^E \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} + \begin{Bmatrix} d_{31} \\ d_{32} \\ 0 \end{Bmatrix} E_3$$

Engineering Strain

Piezoelectric Strain Constants

Plane Stress Orthotropic Elasto-Piezo-Dielectric Relations

$$D_3 = \begin{bmatrix} d_{31} & d_{32} & 0 \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} + \varepsilon_{33}^T E_3$$

Electric Displacement

Free Dielectric Constant

PLANE STRESS CONSTITUITIVE RELATIONS

Actuator Eqn.
$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{xy} & Q_{yy} & Q_{ys} \\ Q_{xs} & Q_{ys} & Q_{ss} \end{bmatrix} \left(\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix} - \begin{Bmatrix} d_{3x} \\ d_{3y} \\ d_{3s} \end{Bmatrix} E_3 \right)$$

Sensor Eqn.
$$D_3 = \begin{bmatrix} e_{3x} & e_{3y} & e_{3s} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix} + e_{33}^S E_3$$

d_{3x} d_{3y} d_{3s}

E_3
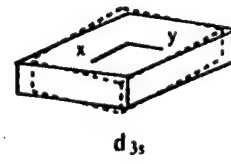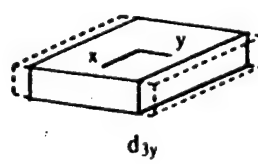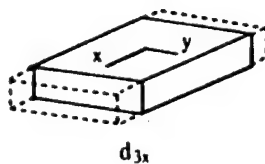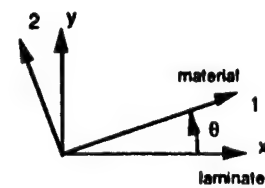
Laminated Plate

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \left(\begin{Bmatrix} \varepsilon_o \\ \kappa \end{Bmatrix} - \begin{bmatrix} \Theta \\ \Gamma \end{bmatrix} \underline{V} \right)$$
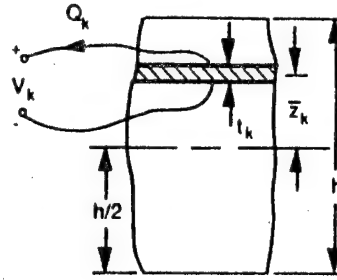
Laminated Beam Wing

$$\begin{Bmatrix} M \\ T \end{Bmatrix} = \begin{bmatrix} EI & -K \\ -K & GJ \end{bmatrix} \left(\begin{Bmatrix} \phi' \\ \theta' \end{Bmatrix} - \begin{Bmatrix} \Gamma_\phi \\ \Gamma_\theta \end{Bmatrix} E_3 \right)$$
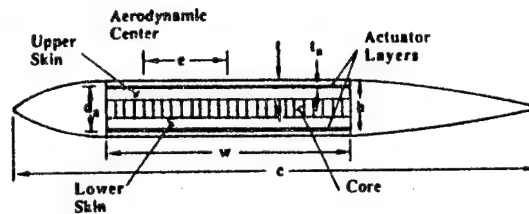
UNIFORM WING IN PURE TORSION
Differential Equation Model

DE: $\quad \theta'' + \lambda^2 \theta = \lambda^2 \theta_o \quad ; \quad \lambda^2 = q \dfrac{ceL^2}{GJ} a_o$
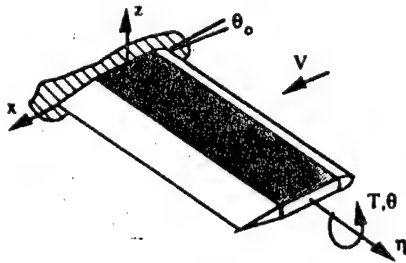
BC: $\quad \theta(0) = 0$

$\qquad\quad \theta'(1) = \Gamma_\theta E_3 L$

Feedback: $\quad E_3 \propto \theta'(0) \quad \Rightarrow \quad \theta'(1) = K_p \theta'(0)$

Solution: $\quad \theta(\eta) = \left[\dfrac{\sin \lambda}{\cos \lambda - K_p} \sin \lambda\eta + \cos \lambda\eta - 1 \right] \theta_o$

Lift Effectiveness: $\quad \dfrac{L_F}{L_R} = \dfrac{\sin \lambda \, (1 - K_p)}{\lambda \, (\cos \lambda - K_p)}$

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LIFT EFFECTIVENESS CONTROL
Pure Torsional Deformation

$$\bar{q}_T = \frac{4\lambda^2}{\pi^2}$$
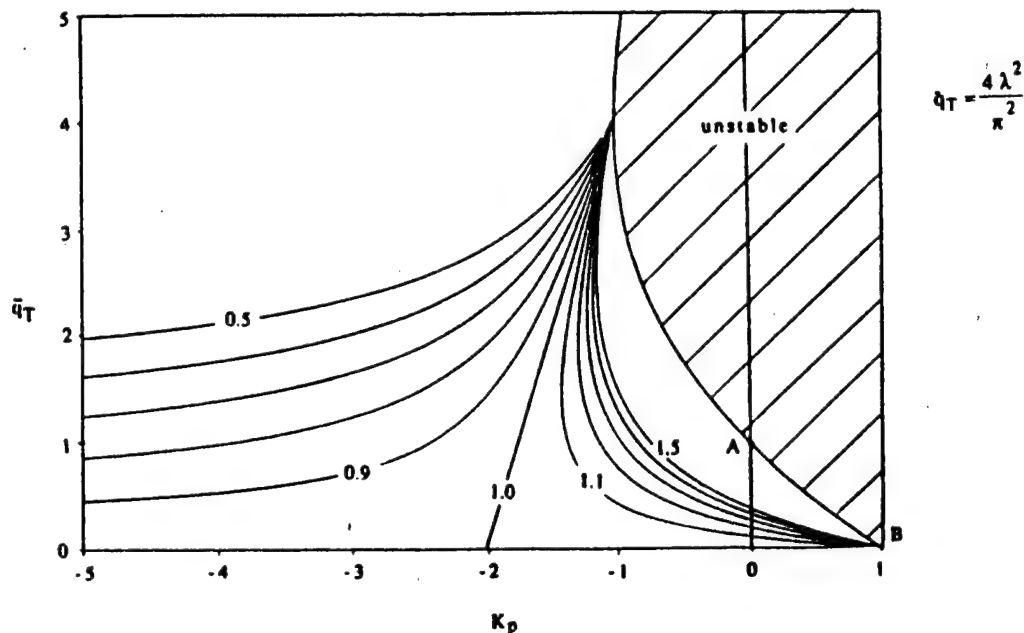
PIEZOELECTRIC MATERIAL LIMITATIONS

Electric Field Limitation $\qquad E_{3min} \le E_3 \le E_{3max} \quad ; \quad E_3 = \frac{K_p}{\Gamma_\theta L} \theta'(0)$

Applied Field $\qquad E_3 = \frac{K_p}{\Gamma_\theta L} \frac{\lambda \sin \lambda}{\cos \lambda - K_p} \theta_o \quad \Rightarrow \quad \frac{\Gamma_\theta E_3 L}{\theta_o} = \frac{K_p \lambda \sin \lambda}{\cos \lambda - K_p}$

Constant Lift Condition $\qquad \theta_o = \frac{W}{qSa_o} \frac{\lambda (\cos \lambda - K_p)}{\sin \lambda (1 - K_p)} \quad \Rightarrow \quad \frac{\Gamma_\theta E_3 L}{\frac{1}{2}\frac{We}{GJ}L} = \frac{K_p}{1-K_p}$

Constant Lift Strength Parameter $\qquad S_L = \frac{\Gamma_\theta E_3 L}{\frac{1}{2}\frac{We}{GJ}L} = 4 \frac{(e_{3s}E_3)\frac{t_a}{h}\frac{d_a}{h}\frac{w}{c}\left(\frac{h}{c}\right)^2}{\frac{W}{S}\frac{L}{c}\frac{e}{c}}$

Active aeroelasticity

S_L

$-.8$ $-.6$ $-.4$ $-.2$ 0 1.0
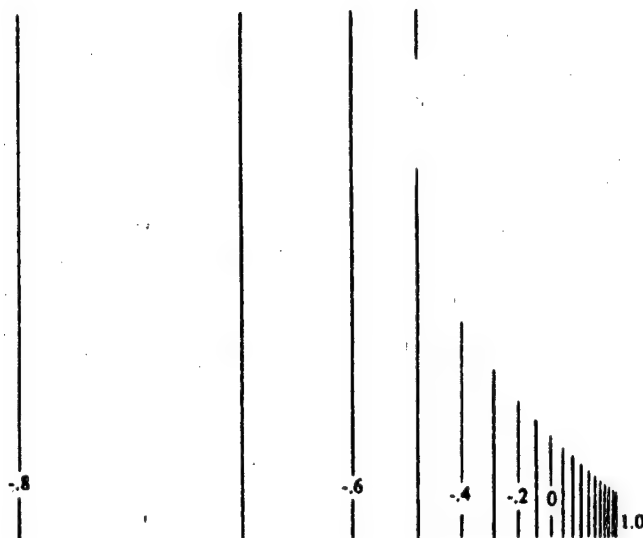
$$S_L = \frac{K_p}{1 - K_p}$$

ADAPTIVE WING DESIGN
Pure Torsional Deformation

$\frac{W}{S}$

$\left(\frac{W}{S}\right)_{max}$

0

$\left|\frac{e_{3s}E_3^{\cdot}}{(S_L)_{req}}\right|$ $\left|\frac{e_{3s}E_3}{S_L}\right|$

$$\frac{W}{S} = \left[4 \; \frac{\frac{t_a}{h} \frac{d_a}{h} \frac{w}{c} \left(\frac{h}{c}\right)^2}{\frac{L}{c} \frac{e}{c}} \right] \left(\frac{e_{3s}E_3}{S_L}\right)$$
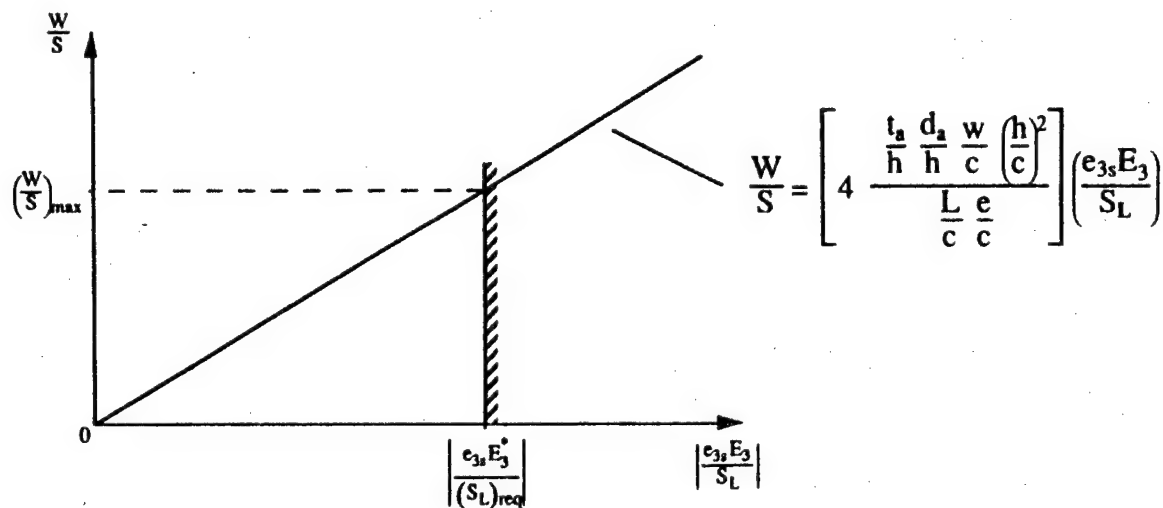
Material Requirements : $e_{3s}E_3^{\cdot}$

Performance Requirements : $(S_L)_{req}$

$$(S_L)_{req} = \frac{\lambda \cos \; \lambda \; \frac{L_F}{L_R} - \sin \; \lambda}{\lambda \; \frac{L_F}{L_R} (1 - \cos \; \lambda)}$$

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Flexible Wing

Rigid Wing

A-A

A-A

(a) **Wash-Out**

(b) **Wash-In**

$$\eta_{EA} = \left(\frac{y}{2}\right) \frac{GJ \sin \Lambda}{EI \cos^2\Lambda + GJ \sin^2\Lambda}$$

Streamwise Flexural Axis

$$\eta_{EA} = \left(\frac{y}{2}\right) \frac{(GJ \sin \Lambda - K \cos \Lambda)}{EI \cos^2\Lambda - K\sin2\Lambda + GJ\sin^2\Lambda}$$

η_{EA}

Λ

y

Reference Axis

y

**Streamwise Flexural Axis Coordinates
for Swept Wings**

Lift Effectiveness Control
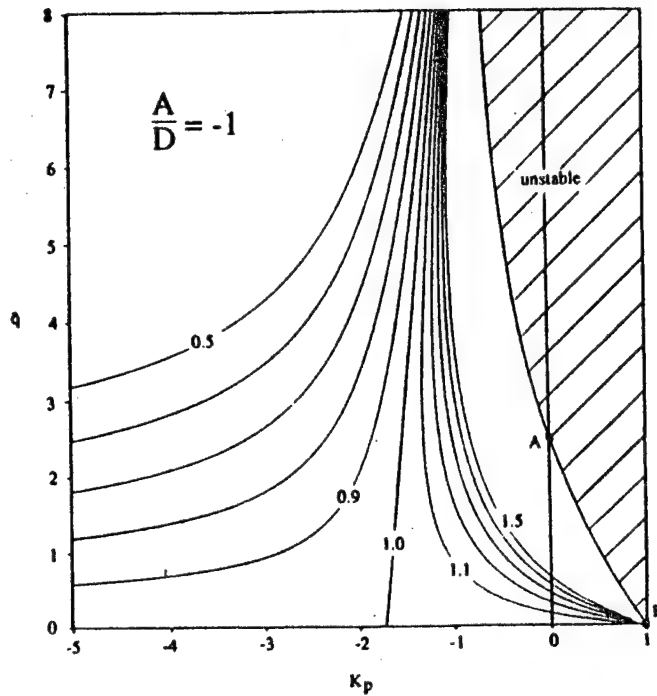
$$\hat{q} = \sqrt{A^2 + D^2}$$

$$\frac{A}{D} = \frac{e}{L} \frac{EI - K\tan\Lambda}{GJ\tan\Lambda - K}$$

SWEPT WING WITH BENDING AND TORSION
Constant Lift Strength Parameter:

$$S_L = 4 \frac{\left[(K - GJ\tan\Lambda)e_{3x} + (EI - K\tan\Lambda)e_{3s}\right] E_3 \frac{t_a}{h} \frac{d_a}{h} \frac{w}{c} \left(\frac{h}{c}\right)^2}{\frac{W}{S} \frac{L}{c} \sqrt{\left(\frac{e}{c}\right)^2 (EI - K\tan\Lambda)^2 + \left(\frac{L}{c}\right)^2 (GJ\tan\Lambda - K)^2}}$$

Active aeroelasticity

S_L
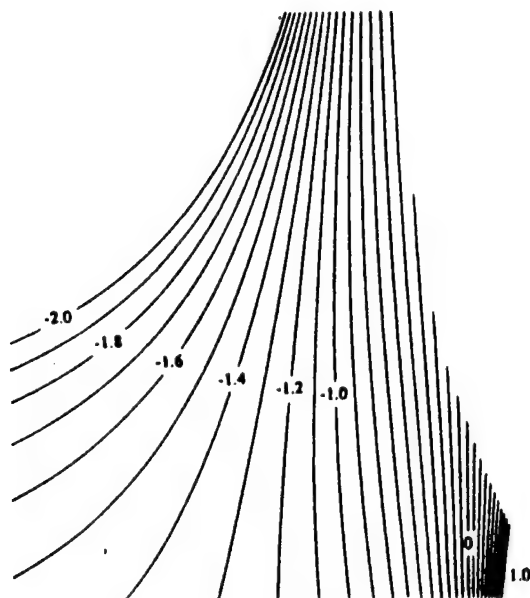
$$S_L = \frac{K_p}{q \frac{L_F}{L_R}} \frac{\alpha_c'(0)}{\theta_0}$$

UAV WING EXAMPLE
Wing Loading vs. Actuator Strength

Maximum Actuator Layer Thickness

Monolithic PZT $S_L = 0.5$

$\frac{W}{S}$ (psf)

$\frac{t_a}{h}$
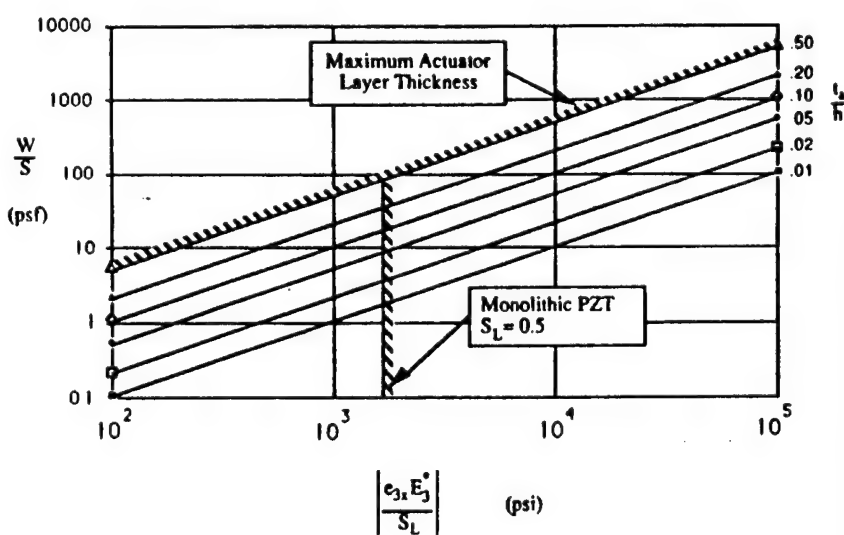
$\left| \frac{e_{3x} E_3^\circ}{S_L} \right|$ (psi)

Wing Parameters

AR: 6.25

Λ: 40°

h/c: 8%

w/c: 0.50

e/c: 0.10

R: 1.0

A/D: 0.0146

Tailored wing actuator effectiveness

$$\text{slope} = 4\left(\frac{t_a}{h}\frac{d_a}{h}\right)\frac{\frac{w}{c}\left(\frac{h}{c}\right)^2}{\left(\frac{L}{c}\right)^2}$$

Maximum Wing Loading

Material Limit

$\frac{W}{S}$
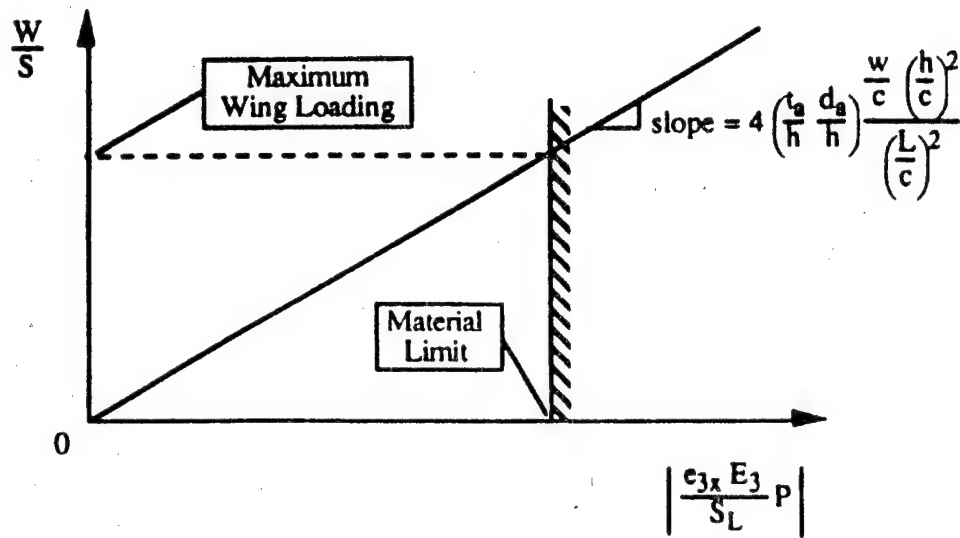
$\left|\frac{e_{3x}E_3}{S_L}P\right|$

$$\frac{W}{S} = 4\left(\frac{t_a}{h}\ \frac{d_a}{h}\right)\frac{\frac{w}{c}\left[\frac{h}{c}\right]^2}{\left[\frac{L}{c}\right]^2}\ \left|\frac{e_{3x}E_3}{S_L}\ P\right|$$

$$P = \cfrac{1}{\sqrt{1+\cfrac{(1-\psi\sqrt{R}\ \tan\Lambda)^2}{(\psi\sqrt{R}-R\tan\Lambda)^2}\left[\frac{e}{L}\right]^2}}$$

Conclusions - static wing control

❑ **Actuator effectiveness is restricted by vehicle size (W/S)**

❑ **Actuator effectiveness can be increased by combining laminate tailoring with effective materials (P factor)**

Microservoelastic actuation

Panel flutter

t=.01 in   8.54 in   20 in

5.71 in

Voltage - 20V/in

15 in   t=.02 in
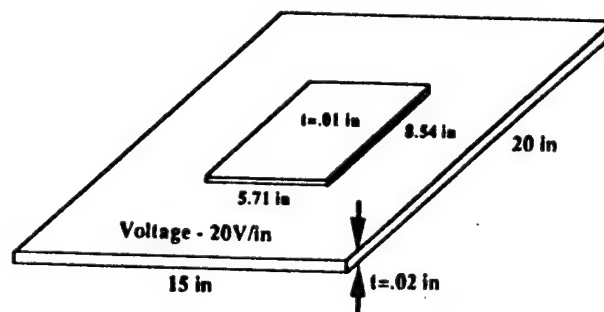
Microservoelastic actuation

transonic airfoils

drag reduction

shock wave attenuation

dynamic stability

General conclusions

Distributed actuators for macroactuation can provide "stiffness on demand" for some practical aeroelastic uses.

Microactuation has not been examined to any large extent.

SECTION III

TECHNOLOGY NEEDS FOR RESEARCH
IN
AERONAUTICAL STRUCTURAL MECHANICS

Explanations

of

Problems, Unknowns, and Science Issues

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1. Introduction

This paper is an interim progress report for a study by the author of the needs for inhouse research within the Structures Division of the Flight Dynamics Directorate of the Air Force's Wright Laboratory. It draws upon the author's experience of over 25 years in structures, structural dynamics and unsteady aerodynamics as well as the opportunities he has had to obtain a broader view by serving as Chief Scientist of the Directorate for the last three years.

The following sections are excerpts from a larger report that lays out an interim summary of some of the requirements in the areas:

- Structural Data, Criteria and Models
- External Loads (Ground-Induced)
- External Loads (Flight Loads and Aeroelasticity)
- Turbulence, Noise and Vibration
- Structural Optimization
- "Smart"/Adaptive Structures
- Hypersonics
- Integration of Structural Analyses and Tests
- Computational Tools and Multidisciplinary Integration

2. Structural Data, Criteria and "Models

2.1 Materials Data Bases - The development of new materials, new structural concepts, new fabrication methods and new aircraft missions requires the orderly development, maintenance and expansion of a data base of materials and structural properties of coupons, elements, panels, components and airframes. However, new materials and fabrication methods are developing faster than our ability to develop an orderly data base. In addition to the usual characteristics related to density, thermal

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properties, strength and stiffness, the data base needs to include features such as initial flaws and defects, and statistical representations of sizes of damage zones near flaws, notches and crack tips - as "virgin" materials and as modified by fabrication processes. Of particular interest is the statistical nature of initial quality and the development and application of standardized methods to assess the growth of damage under combined thermal-mechanical loading and in the presence of Hydrogen or other coolants. The data base also should include the properties under high frequency and random loadings.

2.2 Measured Flight Loads, Flight Load Statistics; Flight Test Dynamics Data Base -Substantial amounts of money and manhours are employed throughout the Air Force to gather statistics on flight loads and maneuver conditions and accelerations. Yet little effort is expended to correlate those statistics (assumed to be correct, but fraught with uncertainties) with flight loads from predictions, wind tunnel test and flight tests. An additional difficulty encountered with operational aircraft is that many were designed to dynamic loads and environments that are insufficient for their current operations. Much of the "design" spectrum is empirical, derived from flight test data from older aircraft such as the F-4 and the F-111. The result is a continuing problem of long-term, high cost maintenance actions, particularly for secondary structures and equipment. Indeed, nearly every inhouse project in the Division to support fleet problems begins with flight tests to measure the "real" environments of dynamic loads and vibrations, as opposed to the "design" environments. The F-15 alone has undergone **separate** flight tests **at different times** for the outer wing panels, vertical tails, horizontal tails and under-fuselage environments. One need is to resume a program of routine flight testing of operational aircraft to measure the detailed dynamic loads, vibrations, acoustics, temperatures, . . . and to prepare criteria for the maintenance and upgrade of those systems as well as for future systems. This will also require an effort to consolidate the data that has been developed for individual weapon system projects, but is not generally known or available outside of the airframe contractor or the government's System Program Office (SPO).

2.3 Full vs Partial Structural Modeling - One of the research issues in Structural Mechanics is the need for efficient (and timely) methods to model aerodynamics, controls and structures for the symmetric, antisymmetric, and asymmetric conditions of flight in enough detail to provide accurate solutions - yet with mathematical models that are compact enough to be used in a fast-paced design process. The mathematical models must be consistent for all phases of design, analysis, operations and trouble-shooting. They need to represent the simplicity of EI, GJ "stick" models at the earliest stages of design and progress systematically to exhaustive finite element models (FEMs) at the later stages. The ideal process would keep the same analytical methods, revolving about a centralized data base, but continually would refine the data as the design progresses. They also must be adaptive to represent the constraints of ground operations and wind tunnel tests as well as the unrestrained conditions of trimmed and maneuvering flight. The need is for a self-consistent set of mathematical models, all of which reflect the necessary overall properties (material properties, inertias, bending stiffness, torsional stiffness, lower vibration frequencies and mode shapes . . .). There is a need for methods to interpret actual inertias and stiffnesses of flight vehicles into mathematical models that reflect the true "non-optimum" properties.

2.4 Uncertain Structural Masses and Inertias - In the earliest stages of design, the designer/analyst creates mathematical models [frequently finite element models (FEMs)] of the (still uncertain) geometry, stiffness, inertia and control system properties of the aircraft under development. The development of those FEMs is a compromise among the known and desired physical properties of the vehicle, the allowed complexity for timely and affordable design and the "art" and skill of the designer/analyst. A major issue results from the need to account for the fact that the FEM may amount to less than half of the mass of the actual vehicle, yet the designer/analyst needs precise estimates of the mass distribution to arrive at accurate inertial forces to predict dynamic response and stability. There is a need for methods to interpret actual inertias and stiffnesses of flight vehicles into mathematical models that reflect the true "non-optimum" properties. Conversely, there is a need for methods to convert the results of optimized mathematical models into actual drawings and properties of flight hardware.

3. External Loads (Ground-Induced Loads)

3.1 Dynamic Response to Damaged and Repaired Runways - While equations and methods exist to calculate the dynamic response of aircraft taxiing on rough and/or damaged runways, there is a significant gap in the conversion of those analytical capabilities into easily understood guidelines and criteria to guide operations for aircraft and airfield operators. The need is for a document to summarize the "Rough Field Capability" of all USAF combat and transport aircraft, as functions of weight, combat loading, speed, acceleration/deceleration vs some standard measures of "roughness" or "softness".

3.2 New Concepts for Landing Gear and Tires - The compilation of the "Rough Field Capability" of all USAF combat and transport aircraft will undoubtedly lead to demands for improvements, and there is some indication (F-15 STOL Demo Program) that significant improvements may be possible with minor changes in landing gear characteristics. Perhaps even greater improvements in rough field operations are possible by reinvigorating basic research in landing gear and tires.

3.3 Skijump Operations - The use of skijumps to reduce takeoff ground roll by USAF fighters is still an idea with untapped potential and possible complications. The theoretical problem is to organize and solve the flight-trajectory and ground-trajectory equations in a clever, nondimensional way in order derive "optimum" skijumps for each aircraft and "standard" skijumps that would offer some benefit all relevant aircraft. The development problem is to assess the new loads on the airframes and landing gears and their effects on durability and structural integrity. The operational problem is to find options for landing as well as takeoff.

4. External Loads (Flight Loads and Aeroelasticity)

4.1 High Incidences and Rates - when the aircraft design envelope calls for high

angles of attack or sideslip, when the pilot can over-ride "g-limiters" in the flight control system to obtain momentarily higher accelerations or when the aircraft generates substantial amount of local turbulence - the accurate prediction of flight loads becomes problemmatical. Recent aircraft developments, expansions and upgrades have encountered the under-prediction of flight loads at high angles of attack and/or sideslip. The causes could be in the steady and unsteady aerodynamics, nonlinearities in the structure or control system or merely inadequate modeling in any of the contributing elements. Eventually we need to couple time-accurate CFD methods with the structure and the flight control system.

4.2 Active Controls - The additional complexity of active controls requires research into the time-domain and frequency-domain modeling of sensors, analog and digital processors and control actuators. It also requires the integration of the aeroservoelastic control system into the overall system of vehicle management for robust, multi-variable systems. In today's design of control systems, the structure usually is considered to be a "given" so that the field of simultaneous design of the structure and the control system is essentially untouched. The whole question of active-suppression of vibrations and flutter needs to be re-opened, due to the recent developments in rapid identification of dynamic systems, control systems and actuation systems.
These conclusions need to be verified by coupling the structural and aerodynamic equations to the flight control laws and piloted simulations. It's possible that aircraft with control systems that provide "care-free" maneuvers will change the statistics of the ground loads and flight loads encounters to a larger percentage of loads just beneath the load limits, resulting in aggravation of any potential fatigue problems. Recent aircraft projects (for instance, the European EFA program) have rationalized the use of lower "factors of safety" on calculated flight loads due to advances in flight control systems which are to provide "care-free" maneuvering and automatically preclude excessive accelerations.

4.3 Unsteady Inviscid Flows - The unsteady aerodynamics of oscillating surfaces has been a historically daunting problem for designer/analysts. For many years the "best" modeling that could be achieved was that for non-viscous, small disturbance, linearized,

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flow. The solution of those equations required many mathematical difficulties to be worked out, but eventually led to "kernel function" (assumed series) and "panel" methods by the late 70s. Today those methods generally are considered to be production engineering tools (in the hands of an expert) for purely subsonic or purely supersonic flows over thin, harmonically oscillating surfaces. In the 70s and 80s, those linearized methods were extended (with modest success) to computational fluid dynamic (CFD) finite-difference methods to non-viscous, small disturbance, (but still) nonlinear, transonic, flows over simple surfaces. However, the promise of CFD has remained frustratingly unfulfilled for realistic unsteady flows of engineering interest to the aircraft designer/analyst. Within the realm of inviscid flows, some of the research issues remaining are: the lack of linearized solution techniques for transient (decaying) motions, the difficulty in modeling (accurately) control surfaces or other discontinuities within a larger lifting surface, uncertainty in the necessary amount of geometric resolution, the affordability of solutions for large-scale problems, the "artfulness" required of the user and the lack of a data base from a well disciplined program of careful, systematic experiments. Probably the most pressing problem is the affordability of (even) reasonably accurate the computations for physically realistic flow problems.

4.4 Unsteady viscous flows - All of the above leaves aside those flow problems which are dominated by viscous effects, such as the steady and unsteady aerodynamic derivatives for oscillating control surfaces or to predict the aeroelastic effects on stability and control (or the maneuver effects on flutter). The "CFD community" and the "aeroelastic community" need to work out the physical, mathematical and computational difficulties of unsteady viscous flows (in a body-fitted coordinate system) over a flexible vehicle with is accelerating along and about any axis. The major issues are the lack of validated turbulence models, the development of the (moving) grid systems, the affordability of physically realistic computations, specification of far-field boundary conditions and the lack of a data base from a well disciplined program of careful, systematic experiments. An early study needs to be made to determine guidelines by which enormous finite-difference meshes for viscous flows can be simplified. Since higher harmonics tend to be integrated out (over successive periods of time) of the "generalized

forcing" functions, there is a possibility that reduced meshes can produce adequate generalized forces for aeroelastic purposes under some conditions.

4.5 Integration of CFD - While extensive research studies of computational fluid dynamics (CFD) are conducted throughout the developed world, very little progress has been achieved in developing CFD methods that are reasonably accurate, yet efficient enough for routine use in conceptual and preliminary design. The usual statement of "wait for bigger computers" probably is not the answer - what is needed is a whole new family of computational solution methods which incorporate the dominant effects on loads, shears, bending moments . . . etc without the need to resolve the flow field into its smallest components. An important (but seemingly trivial) need is for validated, consistent methods to transfer experimental and CFD-predicted pressures and shears from an aerodynamics grid to a structures grid for loads, dynamics or stress analysis - under constraints of self-consistent pressure distributions, shears, overall loads, bending moments and higher "generalized forces". These methods will have to be applicable to the coupled problem of aircraft-pylon-store interaction during carriage, ejection and release

5. Turbulence, Noise and Vibration

5.1 Structural and Acoustic Modeling - One of the major research issues in Acoustics and Sonic Fatigue is the need for efficient (and timely) methods to model the details of the impinging turbulent flow and the multi-mode dynamic response of flight in enough detail to provide accurate solutions - yet with mathematical models that are compact enough to be used in a fast-paced design process. The mathematical models must be consistent for all phases of design, analysis, operations and trouble-shooting.

5.2 Boundary Layer Stability and Transition - Hypersonic vehicles need precise information and control of the stability of the initially laminar boundary layer and its eventual transition to turbulence. The location of transition has drastic effects on local heat transfer as well as drag and the other overall aerodynamic forces and moments. There

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is need for cooperative programs with theoretical and experimental aerothermodynamicists to make substantial improvements in the prediction of boundary layer transition on realistic configurations in hypersonic flight.

5.3 Local Production of Turbulence - This aspect of flight loads may not require methods which apply over the whole aircraft at one time, rather the local production of turbulence from leading edges, inlets, . . . and its effect on downstream structures can be amenable to exhaustive local treatment. Perhaps the greatest need is for improved, experimentally validated CFD "turbulence models" and their applications to the prediction of vortex breakdown for flight loads problems. A related problem that needs additional attention is the extremely turbulent flow in weapon bays, accounting for the effects of stores, suspension equipment, open or closed doors, the state of the upstream boundary layer and overall aircraft attitude.

6. Structural Optimization

6.1 Optimal Geometry - While the subject of much academic research, there does not seem to have much progress in directly optimizing the basic structural geometry of numbers, locations and directions of ribs and spars. Aeroelastic tailoring sizes the wing covers, with an assumed definition of the substructure.

6.2 Flutter Optimization - While the subject of more than a few computer programs, the automated design of realistic aircraft to prevent aeroelastic instabilities is still an "art" and needs to be a topic for much research.

6.3 Dynamically-scaled models - In the later stages of design, the lack of reliable methods to predict transonic effects or viscous effects causes the designer/analyst to use dynamically scaled aeroelastic models in the wind tunnel. Those models are very expensive to design and fabricate, and the necessary "art" resides only in a small (and aging) community of model builders. A fascinating possibility is the potential use of

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"Structural Optimization" methods to create the science base that is necessary to design those sub-scale models to simulate the required stiffness and inertia properties of the aircraft, yet with minimum cost and time.

6.4 Algorithms to Reconfigure a Structure and Control System - Having detected and interpreted flaws, damage, new types of weapons/stores or a decrease in overall structural integrity - there is a need for algorithms to determine the required changes in the applied loads, the resulting "reconfiguration" of the airframe and the flight control system and to alert the pilot to changes in performance or flying qualities of the aircraft.

6.5 Transient or Random Loads - Typically, structural optimization is done with external loads that are static or oscillating sinusoidally. When the oscillation is a growing or decaying one, or if the airloads or thermal loads are transient or random, then the structural optimization process becomes one of trial and error, not necessarily leading to the "best" optimum solution. Recent studies to ". . . increase the fatigue life of a generic vertical tail. . . " required a decision-tree that was external to the formal optimization process and was an ". . . ineffective way to improve fatigue life. " The recommendation was that their was a need to develop methods to include buffet responses and fatigue life **directly** in the formal optimization process.

6.6 Artificial Intelligence . . . - Typical applications of structural optimization by the Air Force (ASOP, FASTOP, ASTROS . . .) rely on the expertise and experience of a collection of engineers, each specializing in loads, strength or aeroelasticity. There is a need for the inclusion of artificial intelligence, expert systems, . . . to reduce the requirements for individually trained experts in each of the disciplines.

6.7 Design Applications - There is a host of problems in aeronautical structures which require the application of structural optimization methods in conceptual and preliminary design. These include: the demonstration (on realistic, large-scale structures) of the optimum mix of materials properties; the definition of the best geometries of

substructures and skins; the definition of required new properties of "tailorable materials"; the definition of best structures in concert with overall aircraft performance, maneuverability, agility, vulnerability and stability and control and the applications to reduce the cost and complexity of manufacturing and maintenance.

7.0 "SMART"/Adaptive Structures

7.1 Propagation of Acoustic and Optical Disturbances In Complex Structure - Propagation of signals from inherent flaws and progressive cracking is easily understood with respect to single disturbances in simple, isotropic structures with simple edge conditions. However, when there are multiple sources in "noisy", complex heterogeneous structure with numerous fasteners and variable edge conditions - algorithms are not yet available which allow the consistent detection, identification and interpretation of the resulting signals. New algorithms need development and evaluation against a series of increasingly difficult problems.

7.2 New Generation of Advanced Sensors - . . . Integration of Sensors in Structures -The integration of sensors and communications in load-bearing structures needs to be understood, particularly with respect to any potential detrimental effect on the structure itself.

7.3 Real-time Identification of Local Structural Flaws - . . . Real-time Identification of Global Structural Deficiencies - . . . Actuation Devices - Are required that are miniature in size and weight, yet have the stiffness, stroke and power to transmit actuation forces to significant structure.

7.4 Real-World Environment - The development of "smart" structures and "smart" vehicles will have to be done within the context of the "real world" of aircraft factories, operating bases, combat, long-term life and repair depots. An assessment is required to determine the potential vulnerability of "smart" structures to the wear and tear

of daily Air Force operations and maintenance. That will need to include development of concepts to design and fabricate those structures to minimize their vulnerability and to evaluate the tradeoffs between cost and complexity.

8. Hypersonics

8.1 Design for Thermal Effects - In the re-emerging field of hypersonic flight, conceptual difficulties remain with respect the design process itself for the design of a structure to transient (and uncertain) thermal conditions, including active-cooling, insulation and the thermal properties of the structure itself. In some cases the skin panel design must come before the design of the primary structural members. There are many possible combinations of insulators and of cooling fluids/gases with structural materials and configurations that could provide safe, efficient, long-life, affordable structures for hypersonic vehicles. Rapid progress is being made in materials developments and fabrication methods under NASP. These need to be expanded to a more general development of feasible concepts for a wide range of follow-on aircraft. It may be feasible to evaluate these concepts in affordable experimental facilities such as the "laser simulator" at the Structures Division. This needs to be done in coordination with a careful predictive program to be assured that the limitations of the experimental methods AND the structural concepts are properly evaluated. Perhaps needless to say, there are no useful methods available to automate the interdisciplinary design process. Fuel slosh effects are beginning to be an important unknown for dynamic loads and stability. Another "surprise" is that it is mathematically impossible to create a dynamically scaled wind tunnel model for dynamic aerothermoelastic effects at any scale other than 100%. The results of highly innovative research will be necessary to even predict the aerothermoelastic stability of hypersonic vehicles (such as the National Aerospace Plane), yet alone to "clear" the vehicles for flight in the conventional sense.

8.2 New concepts to exploit phase change, ablation, transpiration and active-cooling in conjunction with new materials - Major advancements in the capability to

transfer and store heat energy are on the horizon due to new advanced materials and fabrication methods. NASP is supporting many of those concepts, but a systematic program is necessary to design, fabricate and test representative structural components under realistic temperatures and mechanical and aerodynamic loads.

8.3 Creep under Combined Thermo-mechanical Loading - There is a need to predict the deformation of inlets, combustors and nozzles due to transient and repeated thermal and loading environments. Slight changes in the location of the inlet "lip" due to distortion of the inlet or extension of the fuselage could have a deleterious effect on propulsive power and efficiency.

8.4 Devices to Generate Experimental Heating Levels - Infra-red heaters have their temperature limits, and graphite radiant heaters are under development, but still need improvements in cost and durability. Flame-impingement methods, using gases like propane, are under investigation but so far have not shown the desired predictability, cost and effectiveness.

8.5 High Temperature Instrumentation - Attempts are being made to develop strain gages, accelerometers, microphones and pressure transducers (and their attachment methods) that will operate at temperatures up to 2000-3000F. Some results are promising, but perhaps most promising are laser vibrometers which have the potential to replace accelerometers at room and elevated temperatures.

8.6 Sub-scale and/or Early Experimental Simulation - Since fundamental structural materials and configuration for a hypersonic vehicle will depend on the heat transfer capability of the system, there is a need for methods to **simulate** the effects of cryogenic liquids on storage vessels and airframe structure, without resorting to the cost and risk of using liquid hydrogen at remote test sites. Helium and Nitrogen are among the candidate substitutes fluids, but additional data is necessary to evaluate them as simulants for development purposes.

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8.7 Non-intrusive Methods for Applied Heating, Loads and Gathering Data - Even if instrumentation is developed which is adequate at high temperatures, a structures test must still find ways to load a large structure (through the heat sources) in tension and compression.

9. Methods to Integrate Structural Analyses and Tests

9.1 Test data to "update" analytical models - As the aircraft design matures from paper to hardware, or if problems occur in operations, the designer/analyst uses load-deflection tests and ground-vibration tests to verify his estimates of stiffness and inertia. However, the methods to perform those "updates" and to account for the differences between ground-restraints and free-flight are not yet well established or verified by careful experiments. There is a need for a well-controlled theoretical/experimental program to develop and validate a set of "update" methods.

9.2 Rapid Identification of Nonlinear Structures - In the areas of **Vibrations** and **Aeroelasticity** there is a need expressed for the rapid modal identification of nonlinear and linear structures; that need is compounded in this area. Because of the nonlinear and highly damped behavior of tires and landing gear, the coupled response of the aircraft structure (especially the rigid-body modes) to ground disturbances will be nonlinear and highly damped. The need is to be able to identify the mode shapes, frequencies and dampings of those modes from very short time-histories. The problem is compounded by the fact that the dynamic excitation of a landing gear, over any sustained length of time, changes the stiffness and damping of the landing gear. Hence constant amplitude sinusoidal testing is out of the question.

9.3 Integrated Analysis, Design, Test and Reporting - The entire process of structural design, analysis, test and reporting needs to be easier to accomplish. Attention is needed to assigning overall responsibility and authority to one person, in accordance with the assignment of key personnel in the relevant disciplines. It is possible to develop

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methods to routinely: construct the mathematical models of the test structure and the test loads and heating; calculate the stresses, strains and deflections for the test conditions; compare the analytical with the experimental results and automate (as much as possible) the process of documentation, reporting and publication.

10. Computational Tools and Multidisciplinary Integration

10.1 Computer Programs - Within the Air Force community there is definite requirement to have (along with the hierarchy of appropriate finite-element models and supporting data) working versions of the well-known **"integrated"** computer programs NASTRAN, FACES, FASTOP, FASTEX, ADAM, ASTROS, TSO and VAASEL along with supporting data and finite-element models of selected aircraft and components. These computer programs should function independent of the current local computing environment. They should be supported by graphics tools that allow the user to interrogate the intermediate results at all significant points. In addition to the "integrated" versions, each of the programs should be broken into its separate functions, oriented around a data-base and a data-base management system that will allow the user to "pick and choose" the appropriate mathematical models and methods for his engineering problem.

10.2 Multidisciplinary integration - Even assuming all of the issues can be resolved with respect the structural, dynamic and aerodynamic modeling of a vehicle in any speed range, a major hurdle to be overcome is the integration of the multi-disciplinary equations, boundary conditions, data and initial conditions in the time-domain and in the frequency domain. Usually (but not always) the dominant nonlinearities are in the aerodynamics, so that a major issue of affordability is improvement of the speed of CFD methods the prediction of structural performance, vibrations and stability or instability from short time histories of the coupled structural-controls-aerodynamics equations.

10.3 Multidisciplinary Teams/Tools - The Division also needs to approach multi-disciplinary problems with multi-disciplinary teams of experts. There may be a need for

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one master validated computer program (as similar as possible to NASTRAN, ASTROS, etc) and consistent data to provide design predictions of dynamic loads on flexible, actively controlled aircraft - with inputs as diverse as asymmetric landing impact, rough/soft runways, pilot inputs, skijumps, jump-struts, jet-assisted takeoff (JATO), rocket-assisted takeoff (RATO), arrestment, barriers and STOL and V/STOL operations. There is a need for a method to predict flight loads in symmetric, antisymmetric and asymmetric maneuvers - consistent with the related equations and data for aeroservoelasticity and aircraft stability and control.

10.4 Multidisciplinary Approach to Hypersonics - It has to be demonstrated that we can assemble all of the elements of material properties, heat transfer, external and internal loads, stresses, deflections and structural dynamics to safely predict and certify the structural integrity of the airframe of a hypersonic, aeronautical vehicle.

10.5 Multidisciplinary Approach to Aeroservoelasticity - The modeling of the interference and viscous effects for external stores is still an issue, as is their timely clearance for flight (it now takes several months and is usually relegated in problemmatical cases to flight test). Maneuver effects on flutter stability remain an important unknown and usually produce aeroelastic "surprises" as in the effects of symmetric pullups on the flutter of the F-16 and the effects of sideslip on the flutter of the vertical tails of the F-117. The aeroelastic effects on maneuvers and agility are essentially untouched. Further, while the subject of more than a few computer programs, the automated design of realistic aircraft to prevent aeroelastic instabilities is still an "art" and needs to be a topic for much research. Usually (but not always) the dominant nonlinearities are in the aerodynamics, so that a major issue of affordability is the prediction of acoustic, vibration and fatigue of primary and secondary structures.